SOI: 1.1/TAS DOI: 10.15863/TAS

International Scientific Journal

Theoretical & Applied Science

p-ISSN: 2308-4944 (print) **e-ISSN:** 2409-0085 (online)

Year: 2026 **Issue:** 06 **Volume:** 158

Received: 26.06.2026
Accepted/Published: 30.06.2026

https://T-Science.org

Issue Article

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ENERGY ANALYSIS OF THE DRAWING PROCESS OF VARIOUS METALLIC MATERIALS

***Abstract**: This article presents the results of finite element modeling of the drawing process of square metal sheets with an analysis of energy costs for the formation of a thin-walled box-shaped part. Analysis of the energy curves showed that the accumulation of internal energy for all materials has a monotonic character, which corresponds to the consistent development of irreversible plastic deformation with increasing drawing depth. The most intense increase in internal energy for steels and titanium is observed at the initial stage of drawing (0-4 mm), where the primary involvement of the material in plastic flow occurs. For the 5754 deformable aluminum alloy, the maximum increase in internal energy was noted at a drawing depth of 8-12 mm, which indicates a later development of intensive plastic strain. The maximum internal energy was recorded for Ti Grade 4 commercially pure titanium, while the maximum sliding energy was found for S355MC high-strength low-alloy steel. This indicates a different nature of energy consumption: in titanium, resistance to plastic deformation predominates, while in S355MC steel, contact friction plays a significant role.*

***Key words**: drawing, kinetic energy, internal energy, sliding energy, drawing depth.*

***Language**: English*

***Citation**: Chemezov, D., et al. (2026). Energy analysis of the drawing process of various metallic materials. *ISJ Theoretical & Applied Science, 06 (158),* 365-374.

***Soi**: https://s-o-i.org/1.1/TAS-06-158-33 ***Doi**: crossref https://dx.doi.org/10.15863/TAS.2026.06.158.33

***Scopus ASCC**: 2206.*

1. Introduction

Energy analysis of deformation during sheet metal drawing is a method for studying deformation based on the law of energy conservation. It compares the work of external forces (the press) with the energy expended on plastic deformation, overcoming friction and counteracting the pressure.

Accurate energy calculation is complicated by the non-stationarity of the drawing process caused by the following phenomena: variable friction, anisotropy of properties, complex stress state and local thinning of the blank material.

Research in sheet metal forming demonstrates that energy consumption is a key factor influencing the efficiency and environmental friendliness of manufacturing processes. The works of Gao et al. [1] and Santos et al. [3] provide an in-depth analysis of energy consumption in deep drawing processes, identifying dependencies on process parameters and die design. These studies highlight the importance of optimizing such parameters to reduce energy consumption. Ingarao et al. [2] extend the perspective by considering the sustainability of sheet metal forming processes in terms of material loss and energy consumption. When comparing cage forming and stamping, they point out that although cage forming can help reduce material waste, its energy consumption also requires detailed analysis. Chen et al. [5] approach the issue from the perspective of predicting forming limits based on plastic deformation energy. This makes it possible to predict when the material will reach a potential failure point, which is directly related to energy consumption and possible defects. Göschel et al. [4] propose a procedure for balancing energy and material flows in forming processes. It is a comprehensive approach that allows for the visualization and optimization of both energy consumption and waste generation, aiming for full integration and increased efficiency. Cooper et al. [6] conduct a comprehensive analysis of the energy consumption and environmental impacts of five different sheet metal forming processes. Their work provides a comparative assessment, helping to select the most sustainable technologies. Dittrich et al. [7] focus on the energy analysis of cage forming, and Lohse and Weber [9] investigate the efficiency of hydraulic deep drawing presses. Chung and Richmond [8] use an energy method to analyze three-dimensional deep drawing. A recent study by Villalonga et al. [10] provides a detailed analysis of sheet metal forming press energy consumption based on electrical measurements, which allows for the identification of hidden sources of energy losses.

Thus, the study of energy costs for the formability of sheet blanks during the drawing process will allow us to solve a range of technological and economic problems, such as the accurate prediction of defects, reduction of the cost and wear of die parts, and optimization of the technological process. The practical value of the study is the comparison of the kinetic, internal and sliding energies expended during the drawing process of various metallic materials with anisotropic properties.

2. Materials and methods

2.1. Material Selection Rationale

The study employs six strategically chosen materials spanning multiple alloy classes:

- Low-carbon steels (DC05, DC01) – Excellent formability due to low yield strength and high Lankford coefficients (r-values), particularly DC05 steel (r = 2.0) indicating pronounced anisotropic behavior favorable for deep drawing.

- High-strength low-alloy steel (S355MC) – Balances strength (355 MPa) with moderate formability (r = 1.0), representing automotive structural components.

- Austenitic stainless steel (AISI 304) – Combines corrosion resistance with notable strain hardening (E = 196 GPa < steels), complicating springback prediction.

- 5754 deformable aluminum alloy – Low density (2.66 g/cm³) and Young's modulus (70 GPa) necessitate distinct process controls to avoid wrinkling.

- Ti Grade 4 commercially pure titanium – Extreme anisotropy (r = 4.0) and high initial yield strength (500 MPa) challenge conventional forming limits, relevant for aerospace applications.

2.2. Numerical Modeling Methodology

- Software Validation: LS-DYNA's explicit solver is industry-standard for nonlinear transient analyses, with material used given the transverse anisotropy data.

2.2.1. Tooling Geometry:

- Punch-die clearance (2.5 mm) maintains a 3.125× thickness ratio, preventing both excessive thinning and buckling.

- Generous 40 mm corner radii reduce stress concentrations below 80% of material UTS (critical for Ti Grade 4 commercially pure titanium).

2.2.2. Process Parameters:

- Constant Z-axis velocity implies quasi-static conditions (strain rates <0.1/s), justified by neglecting strain-rate effects in provided material data.

- 20 mm draw depth achieves sufficient plastic strain (>0.2) for evaluating thinning distribution without risking fracture.

2.3. Material Property Considerations

Key parameters influencing results:

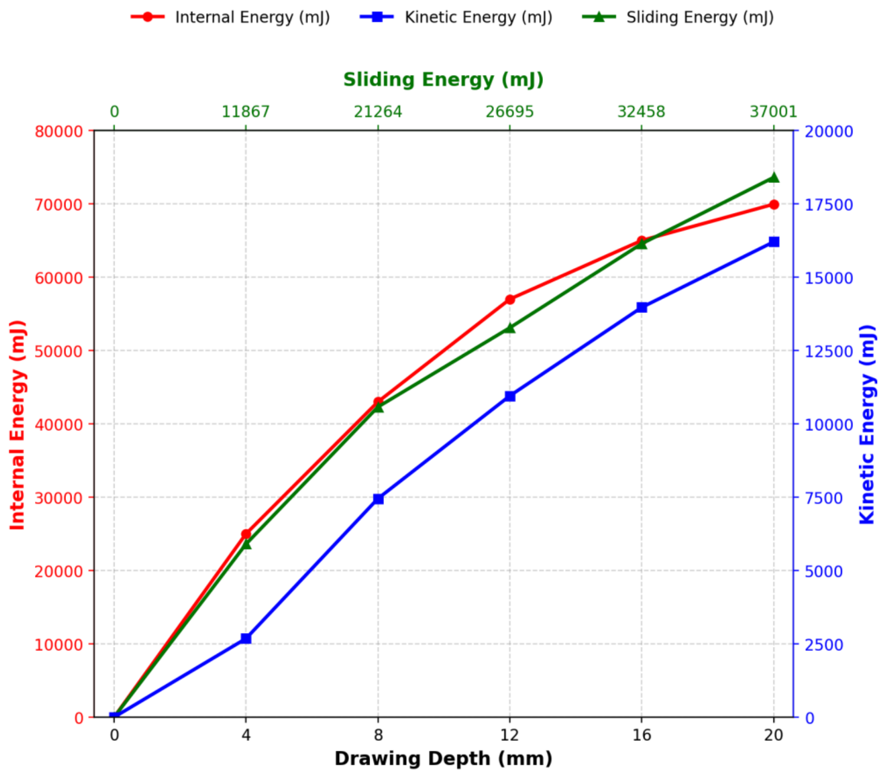
- Tangent modulus values (1.5-2.1 GPa) dominate post-yield behavior, with lower values (e.g., 5754 deformable aluminum alloy at 0.8 GPa) increasing springback susceptibility.

- Poisson's ratio variations (0.29-0.36) affect thickness strain predictions, particularly critical for Ti Grade 4's atypical (0.36).

- Density differences (2.66-7.93 g/cm³) necessitate mass scaling adjustments in explicit dynamics to maintain numerical stability.

3. Results and discussion

The results of the study are presented graphically in Figures 1-6.



Depth (mm)	0	4	8	12	16	20
Time (s)	0.005	0.01	0.015	0.02	0.025	0.03
Internal Energy (mJ)	0	25000	43000	57000	65000	69945
Kinetic Energy (mJ)	0	2681	7452	10955	13970	16203
Sliding Energy (mJ)	0	11867	21264	26695	32458	37001

Figure 1. Energy curves under drawing conditions of DC05 high-quality cold-rolled low-carbon steel.

DC05 high-quality cold-rolled low-carbon steel exhibits softer energy response compared to DC01 steel. The final internal energy is 69945 mJ, which is lower than that of DC01 steel. This is consistent with DC05 steel being a more suitable low carbon steel for deep drawing.

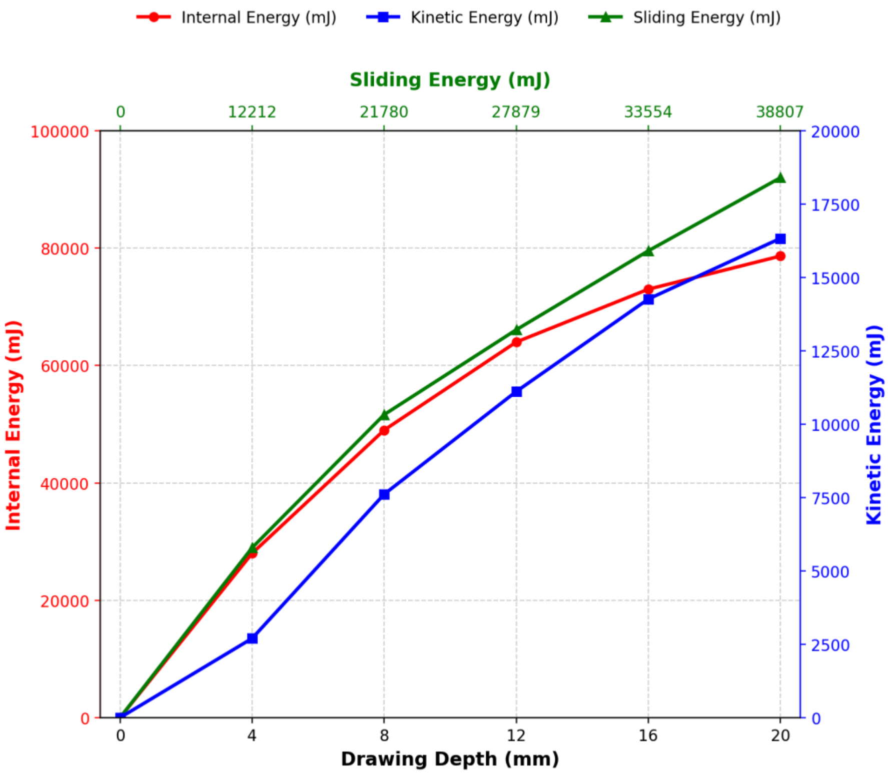
At a drawing depth of 0-4 mm, the internal energy increases to 25,000 mJ. This is less than that of DC01 steel, therefore the material begins to deform plastically more easily. At a drawing depth of 4-8 mm, the increase is 18,000 mJ, then 14,000 mJ at a drawing depth of 8-12 mm. At a drawing depth of 12 mm, the curve becomes noticeably flatter: the increase at a drawing depth of 16-20 mm is only 4945 mJ.

This means that the main plastic work of DC05 steel is also formed in the first half of drawing, but in general the resistance to deformation is lower than that of DC01, AISI 304 and S355MC steels.

The kinetic energy at a drawing depth of 20 mm is 16203 mJ, almost the same as that of DC01 steel. This is an important nuance: despite the lower internal energy, the dynamic component of DC05 steel remains almost at the same level. Therefore, the relative share of kinetic energy in DC05 steel is higher: approximately 23.2% of the internal energy.

The sliding energy reaches 37001 mJ. The ratio of sliding energy to internal energy is approximately 52.9%, which is the highest value among the steels in this set. This means that for DC05 steel, friction has a very significant effect on the energy balance. Despite good formability, the result is highly dependent on contact conditions.

Thus, the material is the most technologically advanced among steels in terms of internal energy, but requires careful setting of friction. If the lubrication, the force of the blank holder, or the roughness of the tool are changed in the model or experiment, it is the DC05 steel that can show a noticeable change in the shape of the sliding energy curve and the distribution of strains.



Depth (mm)	0	4	8	12	16	20
Time (s)	0.005	0.01	0.015	0.02	0.025	0.03
Internal Energy (mJ)	0	28000	49000	64000	73000	78650
Kinetic Energy (mJ)	0	2702	7615	11115	14266	16333
Sliding Energy (mJ)	0	12212	21780	27879	33554	38807

Figure 2. Energy curves under drawing conditions of DC01 structural high-quality carbon steel.

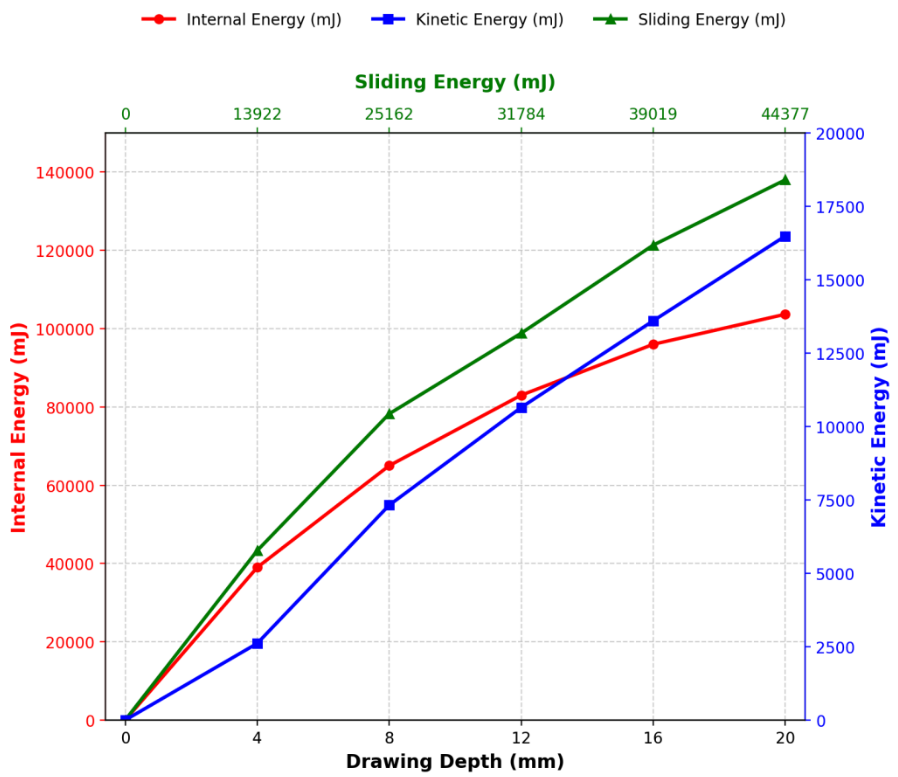
For DC01 structural high-quality carbon steel, a steady increase in all three energy parameters is observed with increasing drawing depth. The most intense increase in internal energy occurs at a drawing depth of 0 to 4 mm: the internal energy increases to 28,000 mJ. This means that already at the initial stage of contact between the punch and the blank, the material actively moves into the region of plastic deformation.

At a drawing depth of 4-8 mm, the increase in internal energy is another 21,000 mJ, meaning the material continues to be actively subject to shape change. With a drawing depth of 8 mm, the energy growth becomes smoother: from 8 to 12 mm the increase is 15,000 mJ, from 12 to 16 mm the increase is 9,000 mJ, from 16 to 20 mm the increase is 5,650 mJ. This indicates a gradual saturation of plastic work: the main part of irreversible deformation is formed in the first half of the process.

Kinetic energy increases from 0 to 16333 mJ. The maximum increase in kinetic energy occurs at a drawing depth of 4-8 mm, where the energy increases by 4913 mJ. This indicates that at the initial stage of drawing the system has the most pronounced dynamic reaction. With further drawing of the material, the increase in kinetic energy is maintained, but becomes more uniform.

The sliding energy reaches 38807 mJ, which is approximately 49.3% of the internal energy. This is a fairly high proportion. Therefore, for steel, contact interaction and friction play a very significant role. In a real process, this means that changing the friction coefficient, the force of the blank holder, or the surface condition of the tool can significantly affect the drawing result.

Thus, the material shows balanced behavior. It requires a fair amount of plastic work, but is not the hardest to draw. In terms of energy response, this steel can be considered as an intermediate option between the softer DC05 steel and the more heavily loaded AISI 304/S355MC steels.



Depth (mm)	0	4	8	12	16	20
Time (s)	0.005	0.01	0.015	0.02	0.025	0.03
Internal Energy (mJ)	0	39000	65000	83000	96000	103670
Kinetic Energy (mJ)	0	2612	7321	10650	13602	16486
Sliding Energy (mJ)	0	13922	25162	31784	39019	44377

Figure 3. Energy curves under drawing conditions of S355MC high-strength low-alloy steel.

S355MC high-strength low-alloy steel is the most energy-loaded material among steels. The final internal energy is 103670 mJ, which is significantly higher than that of DC01, DC05 and AISI 304 steels. This is due to the high initial yield strength and increased resistance to plastic deformation.

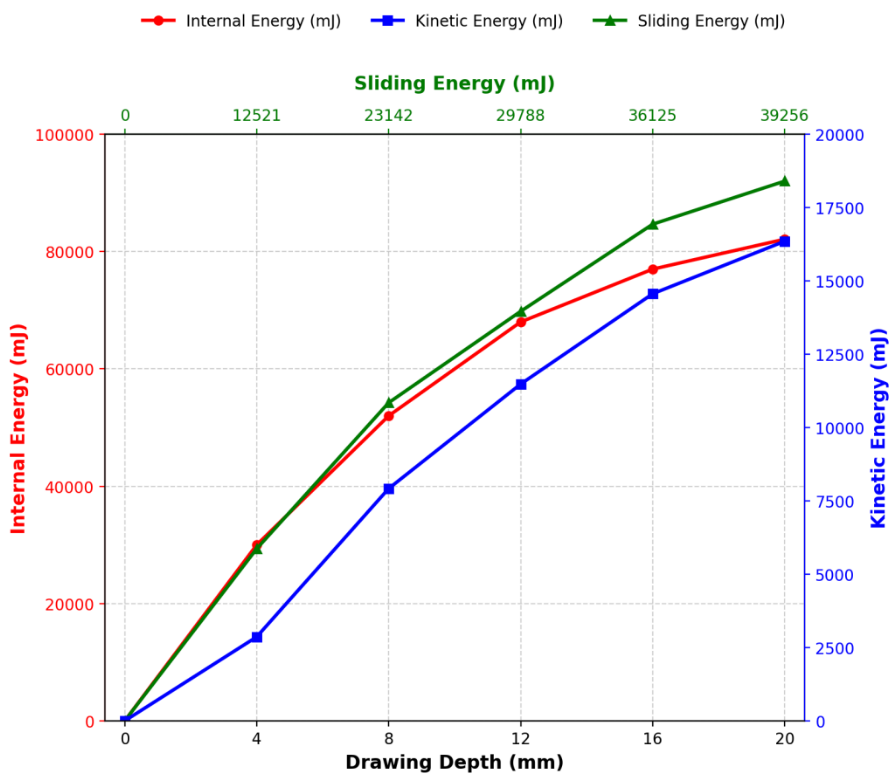
Already at a drawing depth of 0-4 mm, the internal energy reaches 39,000 mJ. This is the highest initial increase among all steels. At a drawing depth of 4-8 mm, the increase is 26,000 mJ, then 18,000 mJ at a drawing depth of 8-12 mm. At a drawing depth of 12 mm, the increase becomes less intense, but remains noticeable: at a drawing depth of 20 mm, another 7670 mJ is added.

The graph shows that S355MC steel requires high deformation work throughout the process. The initial and middle stages of drawing are particularly stressful, when the material begins to be drawn into the die and the walls of the part are formed.

The kinetic energy (16486 mJ) of S355MC steel is the highest among all materials. However, relative to the internal energy it is only about 15.9%. That is, the absolute dynamic energy is high, but against the background of great plastic work it is not decisive.

The sliding energy reaches 44377 mJ – this is the maximum value among all materials. This is a very important result. It shows that S355MC steel has the most intense contact interaction and the highest frictional work. The ratio of sliding energy to internal energy is about 42.8%. Although the relative proportion is lower than that of DC05 steel, the absolute friction value is maximum.

Thus, S355MC steel is the most difficult material to draw among other steels. Drawing this steel requires maximum plastic work and creates maximum contact friction. In the actual process for S355MC steel, the press power, lubrication quality, tool radii, blank holder force, and local stress control in the corner areas of the square part are particularly important.



Depth (mm)	0	4	8	12	16	20
Time (s)	0.005	0.01	0.015	0.02	0.025	0.03
Internal Energy (mJ)	0	30000	52000	68000	77000	82101
Kinetic Energy (mJ)	0	2865	7921	11483	14561	16351
Sliding Energy (mJ)	0	12521	23142	29788	36125	39256

Figure 4. Energy curves under drawing conditions of AISI 304 austenitic stainless steel.

AISI 304 austenitic stainless steel has a higher internal energy level than DC01 and DC05 steels. The final value is 82101 mJ. This is explained by the fact that stainless steel is characterized by a more pronounced resistance to plastic deformation and the ability to the strain-hardening capacity.

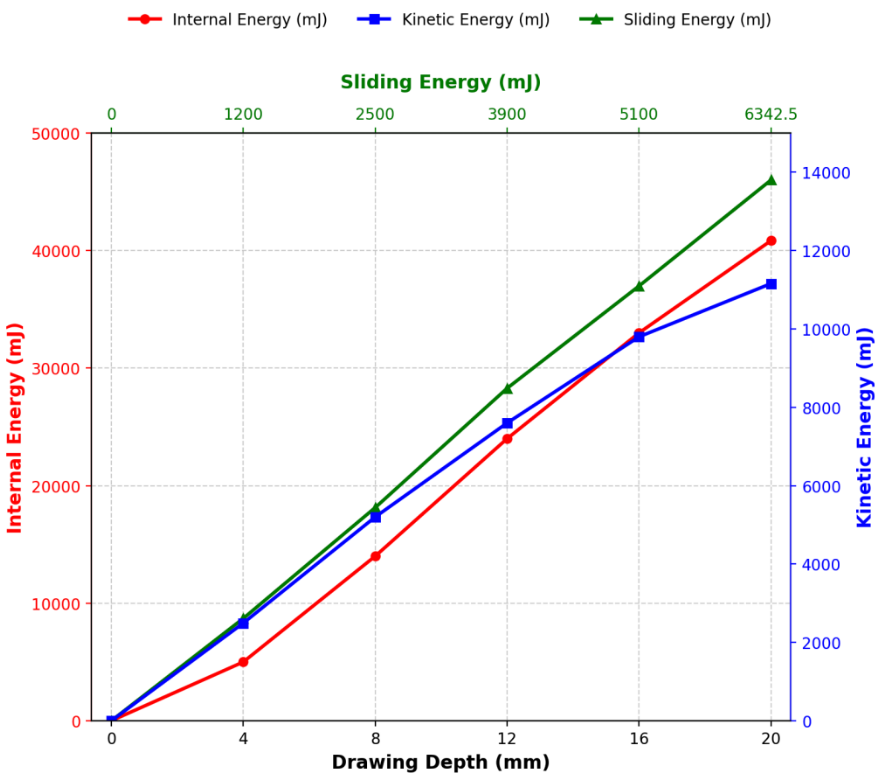
At a drawing depth of 0-4 mm, the internal energy increases to 30,000 mJ, that is, the initial deformation resistance is higher than that of DC01 and DC05 steels. With a drawing depth of 4-8 mm, the increase is 22,000 mJ, and with a drawing depth of 8-12 mm – 16,000 mJ. At a drawing depth of 12 mm, the energy increase slows down. With a drawing depth of 16 to 20 mm, the energy increase is 5101 mJ.

This character of the curve indicates that stainless steel actively resists deformation at the beginning and middle of the process, and towards the end of drawing the rate of accumulation of internal energy decreases. This may indicate a redistribution of strain along the already formed walls of the part.

The kinetic energy reaches 16351 mJ, which is close to the values of DC01, DC05 and S355MC steels. The ratio of kinetic energy to internal energy is about 19.9%. This is lower than that of DC05 steel and 5754 aluminum alloy, meaning that the dynamic component for stainless steel does not dominate over plastic work.

The sliding energy is 39256 mJ. This is slightly higher than DC01 steel and noticeably higher than DC05 steel. Relative to internal energy, this is about 47.8%. This means that almost half of the internal energy level is comparable to the work of friction. Contact conditions for stainless steel are important, but not as critical in terms of internal energy as for DC05 steel.

Thus, this material is more energy-intensive than DC01 and DC05 steels. The graph shows a steady accumulation of plastic work, a high role of friction and a fairly stable dynamic response. In a technological sense, stainless steel requires greater drawing force and more careful control of contact conditions, especially in the flange area and corners of a square part.



Depth (mm)	0	4	8	12	16	20
Time (s)	0.005	0.01	0.015	0.02	0.025	0.03
Internal Energy (mJ)	0	5000	14000	24000	33000	40842
Kinetic Energy (mJ)	0	2492	5200	7600	9800	11157
Sliding Energy (mJ)	0	1200	2500	3900	5100	6342.5

Figure 5. Energy curves under drawing conditions of 5754 deformable aluminum alloy.

5754 deformable aluminum alloy has the lowest internal energy (40842 mJ) among all six materials. This indicates a relatively low work of plastic deformation. The material is easier to form than steels and titanium.

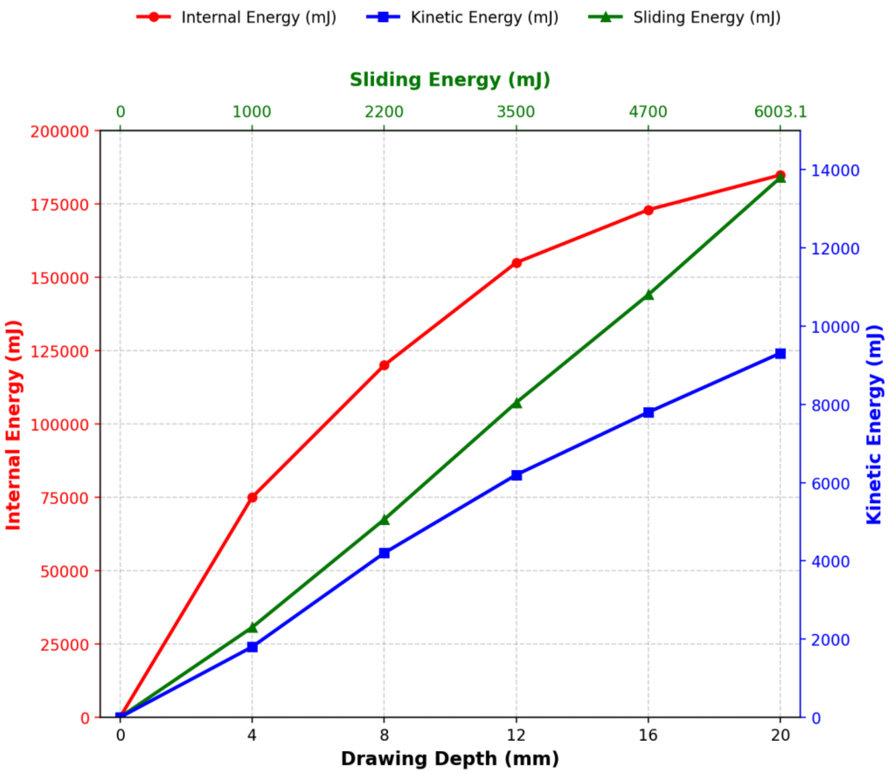
Unlike steels, the initial increase in internal energy of an aluminum alloy is low. At a drawing depth of 0-4 mm, the energy increases only to 5,000 mJ. Then the energy growth becomes more active depending on the depth of sheet drawing: from 4 to 8 mm the increase is 9,000 mJ, from 8 to 12 mm – 10,000 mJ, from 12 to 16 mm – 9,000 mJ, from 16 to 20 mm – 7842 mJ.

This means that the aluminum alloy begins to actively accumulate plastic energy not immediately, but after the initial contact and the transition to a more advanced stage of drawing. Its most active stage is the middle zone of the process, at approximately a drawing depth of 8-12 mm.

Kinetic energy reaches 11157 mJ. In absolute terms this is less than that of steels, but in terms of internal energy it is about 27.3% – the highest relative value among all materials. This is an important nuance: for an aluminum alloy, the dynamic component of the calculation is most noticeable relative to the plastic work.

The sliding energy is 6342.5 mJ, which is much less than that of steels. The ratio of sliding energy to internal energy is about 15.5%. Therefore, in this model, friction plays a significantly smaller role for the aluminum alloy than for steels.

Thus, this material has low energy consumption for drawing, but an increased relative dynamic component. This means that in LS-DYNA for aluminum it is especially important to control the punch speed, the system mass and the ratio of kinetic energy to internal energy. From a technological point of view, the material is easier to deform, but can be sensitive to deformation localization and wrinkling.



Depth (mm)	0	4	8	12	16	20
Time (s)	0.005	0.01	0.015	0.02	0.025	0.03
Internal Energy (mJ)	0	75000	120000	155000	173000	184850
Kinetic Energy (mJ)	0	1800	4200	6200	7800	9310.6
Sliding Energy (mJ)	0	1000	2200	3500	4700	6003.1

Figure 6. Energy curves under drawing conditions of Ti Grade 4 commercially pure titanium.

Ti Grade 4 commercially pure titanium has the highest internal energy level (184850 mJ) of any material. This is the main distinguishing result. The internal energy of titanium is more than twice that of DC01 and AISI 304 steels, and more than four times that of 5754 deformable aluminum alloy.

At a drawing depth of 0-4 mm, the internal energy reaches 75,000 mJ. This is an extremely high initial increase. It shows that titanium immediately exhibits very strong resistance to the onset of plastic deformation. At a drawing depth of 4-8 mm, another 45,000 mJ is added, then 35,000 mJ at a drawing depth of 8-12 mm. At a drawing depth of 12 mm, the increase in internal energy becomes less sharp, but remains significant.

This character of the curve shows that titanium requires a very large amount of plastic deformation work at all stages of the process. In this case, the main part of the energy is accumulated in the first half of the drawing process.

The kinetic energy is 9310.6 mJ, which is one of the lowest values among all materials. The ratio of kinetic energy to internal energy is only about 5.0%. This suggests that the process for titanium in terms of energy balance is closest to the predominance of plastic work over the dynamic component.

The sliding energy is 6003.1 mJ, which is also the minimum level together with aluminum alloy. The ratio of sliding energy to internal energy is about 3.2%. This is a key nuance: for titanium, the main contribution to energy costs is not related to friction, but to the resistance of the material itself to plastic deformation.

Thus, titanium is the heaviest material in terms of internal deformation energy, but not in terms of friction or dynamics. Its behavior is determined by high strength, strong anisotropy and resistance to plastic flow. When drawing titanium, increased forming forces, high residual stresses and high demands on tool strength should be expected.

4. Conclusion

If we consider the energy consumption of drawing based on internal energy, then the order of drawing materials is as follows:

Ti Grade 4 commercially pure titanium > S355MC high-strength low-alloy steel > AISI 304 austenitic stainless steel > DC01 structural high-quality carbon steel > DC05 high-quality cold-rolled low-carbon steel > 5754 deformable aluminum alloy.

If we consider the work of friction in terms of sliding energy, then the order of drawing is different:

S355MC high-strength low-alloy steel > AISI 304 austenitic stainless steel > DC01 structural high-quality carbon steel > DC05 high-quality cold-rolled low-carbon steel > 5754 deformable aluminum alloy > Ti Grade 4 commercially pure titanium.

If we evaluate the dynamic component by kinetic energy, the steels are very close to each other, and the aluminum alloy and titanium have smaller absolute values:

S355MC high-strength low-alloy steel ≈ AISI 304 austenitic stainless steel ≈ DC01 structural high-quality carbon steel ≈ DC05 high-quality cold-rolled low-carbon steel > 5754 deformable aluminum alloy > Ti Grade 4 commercially pure titanium.

The main interpretation of the graphs presented is that different materials consume energy differently. For steels, not only plastic deformation but also friction plays a significant role. The plastic work of an aluminum alloy is small, but the relative dynamic component is noticeable. In titanium, almost all the energy goes into the internal work of deformation, and the contribution of friction and kinetics is small compared to the internal energy.

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