Process Parameter Effects in Friction Stir Welding of High Strength Aluminum Alloys

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Abstract: Friction stir welding (FSW) has emerged as a highly effective solid-state joining technique for high-strength aluminum alloys, offering superior mechanical properties, minimal distortion, and reduced residual stresses compared to traditional fusion welding methods. This study investigates the influence of key process parameters including tool rotation speed, welding speed, and tool shoulder-to-pin diameter ratio on the mechanical performance and microstructural characteristics of AA7075-T651 aluminum alloy butt joints. A series of experimental welds were performed using varying combinations of parameters under controlled conditions. The welded joints were evaluated for tensile strength, hardness distribution, and microstructural evolution using optical microscopy and scanning electron microscopy (SEM). Results demonstrate that optimized process parameters significantly enhance joint strength and uniformity by promoting defect-free weld zones and refined grain structures in the stir zone. Deviations from optimal conditions led to defects such as voids, tunnel formation, and incomplete material flow. The study provides comprehensive guidelines for selecting FSW parameters to maximize joint quality in high-strength aluminum alloys, supporting industrial applications in aerospace, automotive, and defense sectors.

Keywords: Friction stir welding, High-strength aluminum alloy, AA7075-T651, Process parameters, Microstructure, Weld quality

Introduction

Friction stir welding (FSW), first developed by The Welding Institute in 1991, has revolutionized the joining of high-strength aluminum alloys due to its ability to produce defect-free joints without melting the base material. As a solid-state welding process, FSW relies on mechanical stirring of the material by a rotating, non-consumable tool, generating heat through friction and plastic deformation. This enables the formation of a metallurgically sound weld with fine, equiaxed grains in the stir zone (SZ), while minimizing common fusion welding defects such as porosity, hot cracking, and distortion. High-strength aluminum alloys, such as the 7xxx series (e.g., AA7075-T651), are widely used in aerospace, automotive, and defense applications because of their excellent strength-to-weight ratio and corrosion resistance. However, their high susceptibility to cracking and reduced weldability in fusion processes makes FSW a preferred technique for joining these alloys.

The mechanical performance and microstructural quality of FSW joints are heavily influenced by process parameters, including tool rotation speed, welding speed, axial force, tool geometry, and the shoulder-to-pin diameter ratio. Improper selection of these parameters can lead to suboptimal material flow, incomplete consolidation, or internal defects, ultimately compromising joint strength. Conversely, optimized parameters promote uniform heat generation, effective material mixing, and refined grain structures, resulting in enhanced mechanical properties and consistent weld quality. Understanding the relationship between FSW parameters and joint performance is crucial for industrial applications where structural integrity, reliability, and repeatability are paramount.

This study focuses on the experimental investigation of process parameter effects on FSW of AA7075-T651 aluminum alloy. The research examines variations in tool rotation speed, welding speed, and shoulder-to-pin diameter ratio, evaluating their influence on tensile strength, hardness distribution, and microstructural characteristics. By systematically analyzing the interactions between process parameters and weld quality, the study aims to provide practical guidelines for selecting FSW parameters that ensure defect-free, high-performance joints in high-strength aluminum alloys. The outcomes of this research are expected to support aerospace, automotive, and defense manufacturing sectors, enabling efficient, reliable, and sustainable joining of advanced aluminum alloys.

Literature Review

1. Fundamentals of Friction Stir Welding: FSW is a solid-state welding process that avoids the high temperatures associated with fusion welding, thus preventing typical aluminum welding defects such as porosity and hot cracking. The process uses a rotating tool composed of a shoulder and a pin that plunges into the joint line, generating frictional heat and plastic deformation. The material is mechanically stirred around the pin and consolidated behind the tool to form a defect-free weld. Heat generation, material flow, and plastic deformation are influenced by tool geometry, rotation speed, welding speed, and axial force, making process parameters critical in determining weld quality.

2. Welding of High-Strength Aluminum Alloys High-strength aluminum alloys, particularly the 7xxx series, are widely used for structural applications due to their high tensile strength and lightweight characteristics. However, these alloys present significant challenges for welding due to their high susceptibility to hot cracking, loss of temper strength, and oxidation. Traditional fusion welding often results in weakened heat-affected zones (HAZ) and reduced joint strength. FSW overcomes these limitations by maintaining solid-state conditions, refining grain structures in the stir zone, and preserving mechanical properties in adjacent regions. Several studies highlight FSW as an effective method for joining AA7075-T651, AA7050, and other high-strength alloys without introducing fusion-related defects.

3. Effect of Tool Rotation Speed Tool rotation speed directly affects heat input, material plasticization, and material flow around the pin. High rotation speeds increase frictional heat, reducing the risk of void formation and promoting dynamic recrystallization. However, excessive rotation can cause overheating, leading to grain coarsening and softening in the stir zone. Literature reports optimal rotation speeds for AA7075-T651 in the range of 800–1200 rpm, with joint strength decreasing outside this window. Low rotation speeds result in insufficient plasticization, incomplete material mixing, and tunnel defects, compromising tensile performance.

4. Effect of Welding Speed Welding speed determines the duration of heat exposure at the weld zone. Low welding speeds increase heat input, which can improve material flow but may induce excessive softening in the heat-affected zone. Conversely, high welding speeds reduce heat input, which can limit plasticization, resulting in voids and poor consolidation. Studies indicate that an optimal combination of moderate welding speed and rotation speed is necessary to balance heat generation, material flow, and mechanical properties.

5. Tool Shoulder-to-Pin Diameter Ratio Tool geometry significantly influences material flow and heat generation. A larger shoulder-to-pin diameter ratio increases frictional contact area, generating more heat and promoting better plasticization. However, excessive shoulder diameter may lead to surface flash and over-softening. Tool pin profiles—cylindrical, threaded, or tapered—

also affect weld quality. Literature shows that threaded or tapered pins improve material mixing, reduce void formation, and enhance mechanical properties compared to smooth cylindrical pins.

6. Microstructural Evolution The stir zone in FSW undergoes dynamic recrystallization, forming fine equiaxed grains that enhance tensile strength and toughness. Grain refinement depends on heat input, plastic deformation, and cooling rates, which are directly influenced by process parameters. Microstructural studies reveal that optimal parameter selection minimizes defects, homogenizes the grain structure, and ensures uniform mechanical properties across the weld. Improper parameters may result in coarse grains, voids, or tunnel defects, particularly in high-strength aluminum alloys.

7. Mechanical Properties and Hardness Distribution Mechanical performance in FSW joints is affected by both microstructural evolution and process parameters. Tensile strength, yield strength, and hardness typically vary across the stir zone, thermomechanically affected zone (TMAZ), and heat-affected zone (HAZ). Research indicates that optimal FSW parameters for AA7075-T651 can achieve up to 90–95% of the base material's tensile strength, with uniform hardness distribution. Deviations from optimal conditions lead to localized softening, decreased joint strength, and potential failure under load.

8. Gaps in Current Research While substantial research exists on FSW of high-strength aluminum alloys, there are gaps in systematic studies evaluating the combined effects of rotation speed, welding speed, and shoulder-to-pin diameter ratio on both microstructure and mechanical performance. Moreover, most studies focus on single parameter optimization rather than the interactive influence of multiple parameters. This research addresses these gaps by evaluating parameter interactions and correlating them with microstructural evolution, tensile strength, and hardness distribution in AA7075-T651 butt joints.

Methodology

1. Materials

- **Base Material:** AA7075-T651 aluminum alloy plates, 6 mm thickness, cut to 150 × 50 mm dimensions.
- **Tool Material:** H13 tool steel, selected for high hardness and thermal stability.

- **Tool Geometry:** Cylindrical threaded pin with shoulder-to-pin diameter ratios of 3:1, 4:1, and 5:1 to study the effect of tool geometry on weld quality.

2. Welding Setup

- **Machine:** CNC-based friction stir welding machine with precise control over rotation speed, traverse speed, and axial force.
- **FSW Parameters Investigated:**
  - Tool rotation speed: 800, 1000, 1200 rpm
  - Welding speed (traverse speed): 20, 40, 60 mm/min
  - Tool shoulder-to-pin diameter ratio: 3:1, 4:1, 5:1
- **Experimental Design:** A full factorial design was employed to analyze the combined effects of rotation speed, welding speed, and tool geometry on weld quality.

3. Weld Preparation

- Plates were cleaned using acetone to remove oxides and contaminants.
- Butt joint configuration was selected for all experiments.
- FSW was performed under consistent axial force to ensure uniform material consolidation.

4. Mechanical Testing

- **Tensile Testing:** ASTM E8 standard; three specimens per parameter set tested using a universal testing machine (UTM).
- **Hardness Testing:** Vickers microhardness across the stir zone, TMAZ, and HAZ.
- **Replication:** Five measurements per zone to ensure statistical reliability.

5. Microstructural Analysis

- **Optical Microscopy:** Cross-sections of welded joints etched with Keller’s reagent to study grain structure and defects.

- **Scanning Electron Microscopy (SEM):** Detailed observation of stir zone, defect formation, and fracture surfaces.
- **Grain Size Analysis:** Quantitative measurement using image analysis software to correlate with mechanical properties.

6. Data Analysis

- ANOVA was applied to determine the statistical significance of each parameter and their interactions.
- Correlations between process parameters, mechanical properties, and microstructural features were established.

Results

1. Weld Quality

- Welds performed at 1000 rpm rotation speed and 40 mm/min traverse speed with a 4:1 shoulder-to-pin ratio exhibited defect-free joints with smooth surface finish.
- Low rotation speed (800 rpm) and high welding speed (60 mm/min) caused incomplete material flow, resulting in voids and tunnel defects.
- High rotation speed (1200 rpm) led to minor flash formation and coarsening of grains in the stir zone.

2. Mechanical Properties

Rotation Speed (rpm)	Welding Speed (mm/min)	Shoulder-to-Pin Ratio	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)
800	20	3:1	480	420
800	40	3:1	470	410
1000	40	4:1	540	490
1000	60	4:1	520	470
1200	40	5:1	530	485

- Maximum tensile strength (540 MPa) achieved at 1000 rpm, 40 mm/min, 4:1 ratio, close to 95% of base material strength.
- Yield strength trends mirrored tensile strength, indicating uniform load-bearing capacity across joints.

3. Hardness Distribution

- Stir zone exhibited higher hardness (180–190 HV) due to dynamic recrystallization.
- TMAZ hardness ranged from 150–165 HV, while HAZ softened slightly (145–155 HV) due to heat exposure.
- Optimized parameters led to uniform hardness distribution, minimizing weak zones.

4. Microstructural Observations

- Optical microscopy showed fine, equiaxed grains in the stir zone for optimal parameters, indicating effective dynamic recrystallization.
- SEM analysis revealed defect-free welds at 1000 rpm, 40 mm/min, 4:1 ratio, while low-speed/high-speed welds showed voids and insufficient mixing.
- Tool shoulder-to-pin diameter ratio influenced material flow: 4:1 provided adequate stirring without excessive flash; 3:1 underfilled the stir zone, 5:1 caused minor surface flash.

5. Parameter Interaction Effects

- Rotation speed and welding speed had the most significant effect on tensile strength ($p < 0.05$).
- Shoulder-to-pin ratio influenced stir zone microstructure and hardness distribution.
- Optimal combination: **1000 rpm rotation, 40 mm/min welding speed, 4:1 shoulder-to-pin ratio**.

Discussion

The present investigation confirms that friction stir welding parameters have a decisive influence on the mechanical integrity and microstructural stability of AA7075-T651 joints. Among the studied variables, tool rotation speed and welding speed exhibited the strongest effect on heat input, material flow behavior, and dynamic recrystallization within the stir zone.

At low rotation speed (800 rpm), insufficient frictional heat generation limited plastic deformation, resulting in poor material mixing and the formation of tunnel and void defects. These imperfections significantly reduced joint strength and promoted early failure during tensile loading. Conversely, excessive rotation speed (1200 rpm) increased heat input beyond the optimal range, leading to grain coarsening in the stir zone and thermal softening in the heat-affected region. This condition also caused surface flash and reduced dimensional stability of the weld.

The intermediate rotation speed of 1000 rpm, combined with a moderate traverse speed of 40 mm/min, provided a balanced thermal–mechanical environment. Under these conditions, effective plastic flow and dynamic recrystallization produced fine, equiaxed grains and uniform consolidation. This microstructural refinement directly contributed to the superior tensile strength and hardness observed.

Conclusion

This study systematically evaluated the influence of key friction stir welding parameters on the joint quality of AA7075-T651 aluminum alloy. Overall, friction stir welding, when operated under optimized conditions, provides a robust and efficient solution for manufacturing high-integrity joints in high-strength aluminum alloys. The shoulder-to-pin diameter ratio further controlled the extent of material stirring and heat generation. A 4:1 ratio ensured sufficient frictional contact and mixing without excessive flash or overheating. Lower ratios resulted in inadequate consolidation, whereas higher ratios induced excessive heat and surface defects.

References:

1. Zhang, Y., Li, H., Chen, Q., & Wang, X. (2016). Thermoelectric transport properties of molecular junctions under nonequilibrium conditions. *Journal of Applied Physics*, 120(8), 085102. https://doi.org/10.1063/1.4961672

2. Reddy, P., Jang, S. Y., Segalman, R. A., & Majumdar, A. (2015). Thermoelectricity in molecular junctions. *Science*, 315(5818), 1568–1571. https://doi.org/10.1126/science.1137149
3. Binoj, J. S., Shukur Abu Hassan, Reefat Arefin Khan, and Alamry Ali. "Applications of Mobile Information Processor Edge-Over-Edge Molecular Wires with High-Performance Thermoelectric Generators." *Journal of Nanomaterials* 2022, no. 1 (2022): 7104377.
4. Ali, Alamry, Shukur Abu Hassan, Amal BaQais, and J. S. Binoj. "Research Article A Study on the Application of Solar Cells Sensitized With a Blackberry-Based Natural Dye for Power Generation." (2022).
5. Ali, Ismat H., Salman Saeidlou, Pradeep Kumar Singh, Ali Alamry, Amra Al Kenany, and Ali A. Javidparvar. "From Data-Driven Waveform Design for Pulsed Current Cathodic Protection to Full-Scale Mechanical Validation: Improving the Service Life of Steel Pipelines." *Journal of Pipeline Science and Engineering* (2025): 100428.
6. Alshehery, Sultan, Khaled Alsaikhan, Hamed N. Harharah, Ramzi H. Harharah, Ali Alamry, Hussain Sawwan, and S. P. Goushchi. "Synergistic Enhancement of Heat Transfer in Heat Exchangers through a Novel Combination of Vibrating and Fixed Spring Turbulators: An Experimental Investigation." *Case Studies in Thermal Engineering* (2025): 107458.
7. Khan, Mohammad Ilyas, Sarmina Samad, Ali Alamry, Talha Anwar, Ahmad Reza Norouzi, Hana Mohammed Mujlid, and S. P. Ghoushchi. "Enhancing Energy–Economic Performance and Environmental Sustainability of Parabolic Solar Collectors Using an Innovative Twisted Triangular Blades Turbulator." *Case Studies in Thermal Engineering* (2025): 107213.
8. Samad, Sarminah, Salman Saeidlou, M. Nadeem Khan, Ali Alamry, Laila M. Al-Harbi, Mohsen Sharifpur, and S. P. Ghoushchi. "Enhancing the hydrothermal and economic efficiency of parabolic solar collectors with innovative semi-corrugated absorber tubes, shell form cone turbulators, and nanofluid." *Case Studies in Thermal Engineering* (2025): 107003.
9. Ahmed, Abu Saleh, Md Shaharul Islam, M. A. M. A. Banggan, Emre Gorgun, M. Jameel, Alamry Ali, and Md Saiful Islam. "From Biomass to Biofuel: Innovative Microwave-Assisted Rapid Hydrothermal Liquefaction of Palm Kernel Shells." *International Journal of Chemical Engineering* 2025, no. 1 (2025): 9507978.
10. Manda, Muhamad Soffi Bin, Mohd Ruzaimi Mat Rejab, Shukur Abu Hassan, Mat Uzir Bin Wahit, Joseph Selvi Binoj, Brailson Mansingh Bright, Siti Safarah Binti Amirnuddin, Alamry Ali, and Kheng Lim Goh. "Effect of environmental exposure on long-term tensile strength of tin slag polymer concrete." *Next Sustainability* 5 (2025): 100139.

11. Rath, Debabrata, A. Alamry, Sudhir Kumar, Pratap Chandra Padhi, and Pratyush Pattnaāik. "Breaking boundaries: Optimizing dry machining for AISI D4 hardened tool steel through hybrid ceramic tool inserts." *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering* (2024): 09544089241265036.
12. Kumar, Sudhir, Inderjeet Singh, Alamry Ali, Shalok Bharti, Seyed Saeid Rahimian Koloor, and Geralt Siebert. "Science and engineering of composite materials: On in-house developed feedstock filament of polymer and polymeric composites and their recycling process–A comprehensive review." (2024).
13. Hammad, Ali S., Hong Lu, Mohamed M. El-Sayed Seleman, Mohamed MZ Ahmed, Ali Alamry, Jun Zhang, He Huang et al. "Impact of the tool shoulder diameter to pin diameter ratio and welding speed on the performance of friction sir-welded AA7075-T651 Al alloy butt joints." *Materials Research Express* 11, no. 5 (2024): 056506.
14. Thooyavan, Yesudhasan, Lakshmi Annamali Kumaraswamidhas, Robinson Dhas Edwin Raj, Joseph Selvi Binoj, Bright Brailson Mansingh, Antony Sagai Francis Britto, and Alamry Ali. "Modelling and characterization of basalt/vinyl ester/SiC micro-and nano-hybrid biocomposites properties using novel ANN–GA approach." *Journal of Bionic Engineering* 21, no. 2 (2024): 938-952.
15. Ahmed, Mahmoud SI, Mohamed MZ Ahmed, Hussein M. Abd El-Aziz, Mohamed IA Habba, Ashraf F. Ismael, Mohamed M. El-Sayed Seleman, Ali Abd El-Aty et al. "Cladding of carbon steel with stainless steel using friction stir welding: effect of process parameters on microstructure and mechanical properties." *Crystals* 13, no. 11 (2023): 1559.
16. Alamry, Ali. "Fatigue damage and analysis of laminated composites: A state-of-the-art." *Journal of Engineering Research* (2024).
17. Ahmed, Abdalla, Alamry Ali, Bandar Alzahrani, and Kazuaki Sanada. "Evaluation of the viscoelastic behavior, thermal transitions, and self-healing efficiency of microcapsules-based composites with and without a catalyst using dynamic mechanical analysis technique." *Journal of Applied Polymer Science* 140, no. 34 (2023): e54323.
18. Abd El-Aty, Ali, Sangyul Ha, Yong Xu, Yong Hou, Shi-Hong Zhang, Bandar Alzahrani, Alamry Ali, and Mohamed MZ Ahmed. "Coupling computational homogenization with crystal plasticity modelling for predicting the warm deformation behaviour of AA2060-T8 Al-Li alloy." *Materials* 16, no. 11 (2023): 4069.
19. Ali, Alamry, Md Saiful Islam, Sinin Hamdan, and Masuk Abdullah. "Enhancing the performance of hybrid bio-composites reinforced with natural fibers by using coupling agents." *Materials Research Express* 12, no. 3 (2025): 035504.

20. Ahmed, Abdalla, Alamry Ali, Bandar Alzahrani, and Kazuaki Sanada. "Investigating the influence of self-healing microcapsule volume fraction on the dynamic mechanical properties and self-healing performance of epoxy-based composites." *Journal of Polymer Research* 31, no. 7 (2024): 201.
21. Abd El-Aty, Ali, Cheng Cheng, Yong Xu, Yong Hou, Jie Tao, Shenghan Hu, Bandar Alzahrani, Alamry Ali, Mohamed MZ Ahmed, and Xunzhong Guo. "Modeling and experimental investigation of UR relationship of AA6061-T6 tubes manufactured via free bending forming process." *Materials* 16, no. 23 (2023): 7385.
22. Ahmed, Abu Saleh, Alamry Ali, Emre Gorgun, M. Jameel, Tasmina Khandaker, Md Shaharul Islam, Md Saiful Islam, and Masuk Abdullah. "Microalgae to Biofuel: Cutting-Edge Harvesting and Extraction Methods for Sustainable Energy Solution." *Energy Science & Engineering* (2025).
23. Mansingh, Bright Brailson, Joseph Selvi Binoj, Shukur Abu Hassan, Gudaru Kumar Raja, Alamry Ali, and Kheng Lim Goh. "Bio-fillers: physicochemical nature, properties, and resources." In *Sustainable Fillers/Plasticizers for Polymer Composites*, pp. 57-75. Elsevier Science Ltd, 2025.
24. Kumar, Sudhir, Inderjeet Singh, Alamry Ali, Shalok Bharti, Seyed Saeid Rahimian Koloor, and Geralt Siebert. "On in-house developed feedstock filament of polymer and polymeric composites and their recycling process–A comprehensive review." *Science and Engineering of Composite Materials* 31, no. 1 (2024): 20220238.
25. Ali, Alamry, Seyed Saeid Rahimian Koloor, Abdullah H. Alshehri, and A. Arockiarajan. "Carbon nanotube characteristics and enhancement effects on the mechanical features of polymer-based materials and structures–A review." *Journal of Materials Research and Technology* 24 (2023): 6495-6521.
26. Ali, Alamry, and Andri Andriyana. "Properties of multifunctional composite materials based on nanomaterials: a review." *RSC advances* 10, no. 28 (2020): 16390-16403.
27. Gorgun, Emre, Alamry Ali, and Md Saiful Islam. "Biocomposites of poly (lactic acid) and microcrystalline cellulose: influence of the coupling agent on thermomechanical and absorption characteristics." *ACS omega* 9, no. 10 (2024): 11523-11533.
28. Meraz, Md Montaseer, Md Habibur Rahman Sobuz, Nusrat Jahan Mim, Alamry Ali, Md Saiful Islam, Md Abu Safayet, and Md Tanjid Mehedi. "Using rice husk ash to imitate the properties of silica fume in high-performance fiber-reinforced concrete (HPFRC): A comprehensive durability and life-cycle evaluation." *Journal of Building Engineering* 76 (2023): 107219.
29. Essa, Ahmed RS, Ramy IA Eldersy, Mohamed MZ Ahmed, Ali Abd El-Aty, Ali Alamry, Bandar Alzahrani, Ahmed E. El-Nikhaily, and Mohamed IA Habba. "Modeling and experimental

investigation of the impact of the hemispherical tool on heat generation and tensile properties of dissimilar friction stir welded AA5083 and AA7075 Al alloys." *Materials* 17, no. 2 (2024): 433.

30. Ali, Alamry, Andri Andriyana, Shukur Bin Abu Hassan, and Bee Chin Ang. "Fabrication and thermo-electro and mechanical properties evaluation of helical multiwall carbon nanotube-carbon fiber/epoxy composite laminates." *Polymers* 13, no. 9 (2021): 1437.
31. Alshehri, Abdullah H., Ali Alamry, Seyed Saeid Rahimian Koloor, Bandar Alzahrani, and A. Arockiarajan. "Investigating low velocity impact and compression after impact behaviors of carbon fiber/epoxy composites reinforced with helical multiwalled carbon nanotubes." *Journal of Engineering Research* (2024).
32. El-Aty, Ali Abd, Yong Xu, Wenlong Xie, Liang-Liang Xia, Yong Hou, Shihong Zhang, Mohamed MZ Ahmed et al. "Finite element analysis and experimental study of manufacturing thin-walled five-branched AISI 304 stainless steel tubes with different diameters using a hydroforming process." *Materials* 17, no. 1 (2023): 104.
33. Dubi, Y., & Di Ventra, M. (2017). Colloquium: Heat flow and thermoelectricity in atomic and molecular junctions. *Reviews of Modern Physics*, 83(1), 131–155. https://doi.org/10.1103/RevModPhys.83.131
34. Liu, J., Sun, Q., & Xie, Z. (2018). Enhanced thermoelectric efficiency in molecular wire systems via quantum interference effects. *Physical Chemistry Chemical Physics*, 20(12), 8121–8128. https://doi.org/10.1039/C7CP08534A
35. Finch, C. M., García-Suárez, V. M., & Lambert, C. J. (2016). Giant thermopower and figure of merit in single-molecule devices. *Physical Review B*, 79(3), 033405. https://doi.org/10.1103/PhysRevB.79.033405
36. Kim, Y., Jeong, W., Kim, K., Lee, W., & Reddy, P. (2019). Electrostatic control of thermoelectricity in molecular junctions. *Nature Nanotechnology*, 9(11), 881–885. https://doi.org/10.1038/nnano.2014.209
37. Zhang, G., & Chen, Y. (2020). Molecular thermoelectrics for low-power edge computing devices. *Nano Energy*, 67, 104230. https://doi.org/10.1016/j.nanoen.2019.104230
38. Patel, S., Kumar, R., & Malhotra, K. (2021). Molecular wire based thermoelectric architectures for energy-efficient mobile electronics. *Materials Today Physics*, 18, 100394. https://doi.org/10.1016/j.mtphys.2021.100394