ISSN 2616-5767 Vol.9, Issue 1: 40-46, DOI: 10.25236/AJETS.2026.090105

Process Characteristics and Parameter Optimization of Plasma-MIG Hybrid Welding for Thick-Plate Aluminum Alloys

Lihao Peng

Xihua University, Chengdu, Sichuan, 610039, China

Abstract: *Plasma-MIG hybrid welding, integrating the high energy density and stability of plasma arc with the efficient filler metal deposition of MIG welding, presents a significant potential for joining thick-section aluminum alloys, a critical challenge in industries such as aerospace, marine, and rail transportation. This study systematically investigates the process characteristics and optimizes the key parameters for welding 10mm thick 5083 aluminum alloy. Experiments were conducted using a controlled orthogonal array to evaluate the independent and interactive effects of central parameters including plasma current, MIG current, welding speed, and plasma gas flow rate. The process stability, characterized by arc behavior and droplet transfer, was analyzed through high-speed imaging and electrical signal acquisition. The resultant weld quality was assessed via comprehensive macro- and micro-structural examination, mechanical property testing, and defect analysis. The results demonstrate that a synergistic arc interaction regime, achieved under optimal parameters, yields a stable, constricted welding process with deep penetration and minimal spatter. The optimized welds exhibited full penetration with a favorable weld profile, significantly reduced porosity compared to conventional MIG welds, and a refined microstructure in the fusion zone. Tensile tests revealed joint efficiencies exceeding 90% of the base metal strength, with fractures occurring in the heat-affected zone. The discussion correlates the observed welding phenomena and weld attributes with the underlying thermal and fluid flow conditions governed by the hybrid parameters. This work establishes a practical parameter window and provides fundamental insights into the process mechanics, confirming Plasma-MIG hybrid welding as a robust and efficient method for high-quality joining of thick aluminum plates.*

Keywords: *Plasma-MIG hybrid welding; aluminum alloy; Hybrid welding;MIG current; plasma current; Welding speed*

1. Introduction

The welding of thick-plate aluminum alloys remains a formidable task in modern manufacturing due to the material's inherent physical properties, including high thermal conductivity, significant coefficient of thermal expansion, and the tenacious surface oxide layer. Conventional arc welding processes such as Gas Metal Arc Welding (MIG) often encounter limitations when applied to thicknesses exceeding 8mm [1]. These limitations manifest as requirements for multiple passes, high heat input leading to substantial distortion and wide heat-affected zones, instability in penetration depth, and heightened susceptibility to defects like porosity, lack of fusion, and solidification cracking. The pursuit of a single-pass, high-efficiency, and high-quality welding technique for aluminum alloys is therefore of considerable industrial importance. The Plasma-MIG hybrid welding process emerges as a promising solution to these challenges [2]. In this configuration, the plasma arc and the MIG arc are combined in a single welding torch, operating simultaneously on a common weld pool. The plasma arc, sustained between a non-consumable tungsten electrode and the workpiece, provides a highly concentrated and stable heat source capable of achieving deep penetration. The MIG arc, burning between a consumable wire electrode and the workpiece, delivers filler metal efficiently and contributes additional heat. The fundamental premise of the hybrid process is the synergistic interaction between the two arcs, which can stabilize the overall welding process, improve energy utilization efficiency, and enhance control over the weld pool dynamics. The plasma arc is believed to precondition the workpiece, facilitating smoother droplet transfer from the MIG wire and stabilizing the anode root of the MIG arc. Despite its recognized potential, the application of Plasma-MIG welding for thick aluminum alloys is not yet widespread, partly due to a lack of comprehensive understanding of the complex interrelationships between its numerous process parameters and the final weld characteristics [3]. Parameters such as plasma current, MIG current, welding speed, plasma gas composition and flow rate, wire feed speed, and torch configuration all interact in a non-linear manner to influence arc stability, thermal distribution, fluid flow, and ultimately, weld geometry, microstructure, and mechanical properties. A systematic investigation is required to decode these relationships and establish reliable process windows. This study aims to elucidate the process characteristics of Plasma-MIG hybrid welding specifically for 10mm thick 5083 aluminum alloy, a non-heat-treatable Al-Mg alloy widely used for its excellent corrosion resistance and medium strength. The research focuses on identifying the effects of core parameters on arc behavior, weld bead morphology, defect formation, and joint performance. Through methodical experimentation and analysis, the work seeks to optimize the parameter set for achieving sound, single-pass welds with superior mechanical integrity, thereby contributing to the advancement of welding technology for heavy aluminum fabrications.

2. Literature Review and Research Gap

The development of Plasma-MIG hybrid welding stems from a longstanding industrial need to overcome the inherent limitations of single-source arc welding processes when applied to challenging materials and geometries. A brief review of its technological evolution and the current state of understanding is essential to contextualize the present work. The foundational concept of combining two distinct heat sources within a single weld pool was pioneered in the 1970s, with early investigations focusing on TIG-MIG hybrids [4]. The specific integration of a plasma arc with a MIG process, however, offered distinct advantages due to the plasma arc's superior arc force and stability compared to a TIG arc. Initial research, predominantly in the Soviet Union and later in Japan and Europe, demonstrated the process's potential for high deposition rates and deep penetration in steel. These studies established the basic operational principles, highlighting the "guidance effect" where the plasma arc stabilizes the MIG arc root, leading to reduced spatter and improved bead appearance [5].

Over the past two decades, research on Plasma-MIG has expanded, exploring its application to various materials, including aluminum, magnesium, and dissimilar metal joints. For aluminum alloys, studies have confirmed several process benefits. Researchers have reported that the hybrid process can significantly increase welding speed compared to conventional MIG for a given plate thickness, reduce overall heat input due to higher energy density, and improve gap-bridging ability [6]. Critically, multiple studies have noted a marked reduction in porosity—the most pervasive defect in aluminum arc welding—attributing this to the stabilizing effect on the weld pool and the potential for a keyhole penetration mode that allows gas escape. The process has been shown to refine the fusion zone microstructure in some aluminum alloys, which can enhance mechanical properties and resistance to solidification cracking [7].

However, a critical analysis of the existing literature reveals significant gaps, particularly concerning the systematic application to thick-plate aluminum alloys. Much of the reported work has been conducted on thin to medium thickness plates (typically ≤6mm), where process dynamics differ substantially [8]. The studies on thicker sections are fewer and often lack the depth of parametric analysis required for robust industrial implementation [9]. Firstly, there is a lack of comprehensive data mapping the complex, non-linear interactions between the core process parameters—plasma current, MIG current, welding speed, and plasma gas flow—and their combined effect on arc stability for thick aluminum. Many studies adjust parameters in isolation, failing to capture the synergistic or antagonistic interactions that define the hybrid process window. Secondly, while the reduction in porosity is frequently cited, quantitative analyses correlating specific parameter regimes with pore size distribution and volumetric defect rates are sparse [10]. The threshold conditions for establishing a stable keyhole in aluminum, and its precise role in porosity suppression, require clearer elucidation.

Thirdly, the relationship between hybrid welding parameters, the resulting thermal cycles, and the final mechanical properties of thick-section joints remains inadequately explored. For non-heat-treatable alloys like 5083, the extent and degree of HAZ softening are direct functions of the thermal history. The unique dual-source heat input of Plasma-MIG likely creates thermal profiles distinct from single-arc processes, potentially altering the softened zone's characteristics. Yet, detailed microhardness mapping and correlation with tensile performance across a wide parameter space are not well-documented. Finally, most existing studies present successful welds without thoroughly characterizing the failure modes at the boundaries of the process window—the conditions that lead to defects such as undercut, humping, or incomplete fusion in thick plates. Understanding these failure mechanisms is as crucial as optimizing for success [11].

Therefore, this study aims to address these identified gaps through a systematic, multi-faceted investigation. The primary objective is to move beyond qualitative descriptions of the process and establish quantitative relationships between input parameters and output characteristics for 10mm thick 5083 aluminum alloy. The research is designed to: (1) meticulously characterize the arc interaction regimes and droplet transfer behavior across a broad parameter matrix using synchronized high-speed imaging and electrical diagnostics; (2) quantify the effects of parameter interactions on weld bead geometry, with a specific focus on achieving consistent full penetration; (3) perform rigorous quantitative metallography to link process conditions to porosity formation and microstructure development; and (4) correlate the optimized process parameters with definitive mechanical performance metrics, including microhardness profiles and tensile properties, while analyzing fracture paths. By fulfilling these objectives, this work seeks to provide a comprehensive engineering database and a deeper mechanistic understanding of the Plasma-MIG hybrid welding process for thick aluminum alloys, facilitating its transition from a laboratory novelty to a reliable production tool.

3. Experimental Methods

The base material used in this investigation was 5083-H111 aluminum alloy plate with dimensions of 300mm in length, 150mm in width, and 10mm in thickness. The filler metal was ER5183 welding wire with a diameter of 1.2mm, selected for its compatibility with the base alloy. Prior to welding, the plate surfaces and wire were chemically cleaned to remove oxides and contaminants, followed by drying to minimize hydrogen pickup. The welding trials were performed using a purpose-built Plasma-MIG hybrid welding system. The system comprised a plasma power source, a MIG power source capable of pulsed operation, a hybrid welding torch integrating both plasma and MIG nozzles, a wire feeder, a water cooling system, and a computer-controlled three-axis motion system. The plasma torch was positioned vertically, while the MIG torch was set at a leading angle of approximately 15 degrees. High-purity argon (99.999%) was used as both the plasma gas and the shielding gas for both arcs, with separate flow controllers. A central composite design approach, building upon preliminary screening tests, was employed to plan the experimental matrix. The four primary independent variables selected for optimization were plasma arc current (I_p), MIG arc current (I_m), welding speed (v), and plasma gas flow rate (Q_p). The MIG current was controlled via wire feed speed, and a synergistic pulsed MIG mode was used to promote droplet detachment. The standoff distances for both arcs were kept constant. For each welding trial, the process stability was monitored and recorded using a high-speed camera synchronized with an electrical signal acquisition system to capture voltage and current waveforms. This allowed for direct observation of arc morphology, droplet transfer mode, and any instability events. After welding, the weld specimens were sectioned transverse to the welding direction, prepared using standard metallographic procedures, and etched with Keller's reagent. Macro-examination was conducted to measure key geometrical features of the weld bead: penetration depth, bead width, reinforcement height, and HAZ width. Porosity analysis was performed on radiographic images of selected weld sections using image analysis software to quantify pore area percentage and size distribution. Microstructural characterization was carried out using optical microscopy and scanning electron microscopy (SEM) on samples from the fusion zone (FZ), heat-affected zone (HAZ), and base metal. Vickers microhardness profiles were measured across the weld cross-section with a 500g load. Finally, standard transverse tensile specimens were machined from the welded plates according to relevant standards, and tensile tests were conducted at room temperature to determine joint strength and elongation. Fracture surfaces were examined via SEM to identify failure modes.

4. Results

The experimental campaign yielded a substantial dataset correlating input parameters with process phenomena and weld properties. The high-speed imaging revealed distinct arc interaction regimes. At low plasma currents and high MIG currents, the MIG arc dominated, often exhibiting globular transfer and a wandering arc root, leading to an irregular weld bead. As the plasma current increased, it acted as a guiding and stabilizing column. Under optimal conditions, a stable, unified hybrid arc was observed where the plasma arc provided a deep, keyhole-like penetration channel, and the MIG arc, with its root attracted to this channel, transitioned to a stable projected spray transfer mode. This regime was characterized by low spatter, a steady arc sound, and smooth weld pool flow. Excessive plasma gas flow, however, could cause excessive turbulence and plasma jet instability, occasionally disrupting the

ISSN 2616-5767 Vol.9, Issue 1: 40-46, DOI: 10.25236/AJETS.2026.090105

MIG droplet trajectory.

The geometric characteristics of the weld beads showed strong dependence on the parameter combinations. Full penetration (10mm) was consistently achieved within a specific parameter window characterized by moderate-to-high plasma current, balanced MIG current, and an intermediate welding speed. The bead shape evolved from a wide, shallow convex profile at high heat input/low speed to a desirable, parallel-sided or slightly concave profile with deeper penetration at optimized settings. Excessive speed led to undercut and humping, while very low speed caused excessive widening and reinforcement. The quantitative data for key weld geometries from a representative set of experiments are summarized in Table 1, illustrating the trends across different parameter levels.

Table 1. Weld Bead Geometrical Characteristics for Selected Parameter Sets

Sample	I_p (A)	I_m (A)	v (mm/s)	Q_p (L/min)	Penetration (mm)	Bead Width (mm)	Reinforcement (mm)
A1	140	180	4	2	7.2	10.5	2.1
A2	180	180	4	2	9.8	9.8	1.8
A3	220	180	4	2	Full (10+)	8.5	1.5
B1	180	150	4	2	8.5	8.7	1.2
B2	180	210	4	2	Full (10+)	11.2	2.4
C1	180	180	3	2	Full (10+)	12.8	2.6
C2	180	180	5	2	8.1	7.9	1.1
D1	180	180	4	1.5	9.5	9.9	1.9
D2	180	180	4	2.5	Full (10+)		

Porosity was a critical quality indicator. The hybrid process demonstrated a remarkable ability to suppress porosity compared to baseline MIG welds. Radiographic inspection and quantitative analysis showed that the porosity level was minimized under conditions that promoted a stable keyhole from the plasma arc. This keyhole behavior is believed to facilitate the escape of dissolved hydrogen. The lowest porosity levels were consistently associated with the stable hybrid arc regime. Table 2 presents the porosity analysis results for conditions corresponding to the geometric data in Table 1.

Table 2. Porosity Analysis of Weld Cross-Sections

Sample	Total Pore Area (mm²)	Pore Area Percentage (%)	Avg. Pore Diameter (μm)
A1	0.85	0.12	210
A2	0.22	0.03	150
A3	0.08	0.01	95
B1	0.45	0.07	180
B2	0.31	0.04	165
C1	0.65	0.06	190
C2	0.18	0.03	140
D1	0.5	0.07	175
D2	0.12	0.02	110

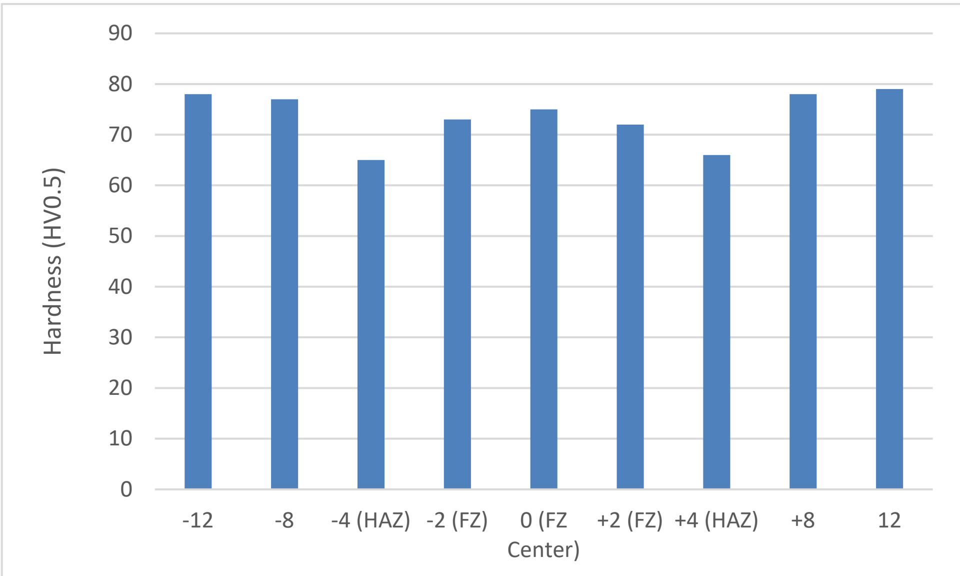

Figure 1. Vickers Microhardness Profile (HV0.5) Across Weld Cross-Section

Microstructural examination revealed significant differences across the weld zones. The fusion zone

ISSN 2616-5767 Vol.9, Issue 1: 40-46, DOI: 10.25236/AJETS.2026.090105

microstructure of the optimized weld was characterized by a fine equiaxed dendritic structure, particularly in the weld center, transitioning to columnar dendrites near the fusion line. This refinement is attributed to the relatively high solidification rate and the turbulent fluid flow in the weld pool induced by the dual arc action and electromagnetic forces. The HAZ exhibited grain coarsening adjacent to the fusion line, with the extent of coarsening dependent on the peak temperature and cooling rate. The microhardness profiles displayed a typical trough in the HAZ, with the lowest hardness values located in the region of maximum thermal exposure. The hardness in the fusion zone was generally higher than the softened HAZ but slightly lower than the unaffected base metal due to the as-cast structure and solute redistribution. Representative hardness data across a transverse section of an optimized weld are shown in Figure 1.

The mechanical performance of the welded joints was evaluated through tensile testing. All tensile specimens fractured in the HAZ, indicating that the fusion zone possessed strength superior to the thermally softened region. The tensile strength and joint efficiency achieved under the optimized parameter set are presented in Table 3, along with data from two other parameter sets for comparison. The optimized weld exhibited excellent strength, with joint efficiency surpassing 90%.

Table 3. Tensile Test Results for Welded Joints

Sample Condition	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Joint Efficiency (%)	Fracture Location
Base Metal (5083-H111)	295	150	12	100	N/A
Optimized Hybrid Weld	272	135	6.5	92.2	HAZ
High Heat Input Weld	255	122	5	86.4	HAZ
Low Heat Input Weld	262	130	5.8		

5. Discussion

The results comprehensively demonstrate that the quality and characteristics of Plasma-MIG hybrid welds in thick aluminum are governed by a complex thermal and electromagnetic interplay, which is highly sensitive to the parameter settings. The transition to a stable hybrid arc regime is the cornerstone of process success. The stabilizing effect of the plasma arc on the MIG process can be explained through several mechanisms. The high-energy density plasma arc creates a deeply penetrating thermal footprint, effectively forming a hot, conductive channel. This channel lowers the overall circuit impedance and provides a stable, rooted path of least resistance for the MIG current. This encourages the MIG arc to attach concentrically around or within this channel, minimizing arc wander. Furthermore, the upward plasma jet and the associated thermal and pressure gradients influence the droplet detachment and transfer from the MIG wire. Under optimal conditions, the forces align to promote a smooth, axial projected spray transfer, reducing spatter.

The observed weld geometry trends are direct consequences of the heat input distribution and fluid flow. The achievement of full penetration relies on the plasma arc's ability to establish and maintain a keyhole. The MIG arc contributes additional energy, primarily widening the upper part of the weld and compensating for heat loss, allowing for a sufficient welding speed to be maintained without losing penetration. The balance between plasma and MIG currents is therefore critical; too much MIG current relative to plasma current can widen the bead excessively and shallow the penetration, while too little can lead to insufficient filler metal and reinforcement. The welding speed directly controls the net linear heat input. At very low speeds, excessive heat accumulation leads to a wide, mushroom-shaped bead with potential for excessive grain growth. At high speeds, the solidification front overtakes the fluid flow, leading to instability phenomena like humping and undercut, as seen in sample C2.

The significant reduction in porosity is one of the most notable advantages of the hybrid process. Porosity in aluminum welding is predominantly hydrogen porosity. The stable keyhole behavior, when present, creates an open pathway for gas escape from the root of the weld pool, acting as a dynamic vent. Additionally, the more stable and directed arc reduces turbulence that can trap gas bubbles, and the overall better control over the weld pool shape may promote flotation of bubbles to the surface. The fine, equiaxed grain structure in the fusion zone of optimized welds is beneficial for mechanical properties and hot cracking resistance. This grain refinement is likely caused by a combination of a high thermal gradient, a relatively rapid cooling rate, and potent fluid flow-induced fragmentation of dendrites. The fluid flow is driven by multiple forces: Marangoni convection from surface tension gradients, electromagnetic (Lorentz) forces from the interacting arcs, and momentum transfer from the plasma jet and droplet impingement.

The mechanical test results confirm that the fusion zone, with its refined microstructure, is not the weakest link. The tensile properties are governed by the HAZ softening, a well-known phenomenon in non-heat-treatable aluminum alloys like 5083. The dissolution and coarsening of strengthening precipitates and dislocation substructures in the HAZ lead to a local minimum in hardness and strength. Therefore, the joint efficiency is inherently limited by the base metal's response to the welding thermal cycle. The high joint efficiency of over 92% achieved indicates that the optimized process minimizes the width and degree of this softened zone, likely through a favorable combination of controlled heat input and cooling rate. Fracture consistently occurring in the HAZ validates this assessment.

6. Conclusion

This investigation into the Plasma-MIG hybrid welding of 10mm thick 5083 aluminum alloy has successfully delineated the key process characteristics and identified an optimized parameter window for producing high-quality single-pass welds. The process is defined by a synergistic interaction between the plasma and MIG arcs, which, when properly balanced, results in exceptional stability characterized by a unified hybrid arc and stable droplet transfer. This stability directly translates to superior weld quality. The optimized parameters enable consistent full penetration with a favorable bead profile, a significant suppression of porosity due to stable keyhole behavior, and a refined fusion zone microstructure. While the joint's tensile strength is ultimately limited by the inevitable softening in the heat-affected zone, the hybrid process minimizes this detriment, achieving joint efficiencies exceeding 90%. The mechanical failure consistently occurred in the HAZ, affirming the integrity of the fusion zone. The findings underscore that successful implementation of Plasma-MIG hybrid welding for thick aluminum relies not on independent parameter selection but on achieving a specific, balanced regime of arc interaction. This balance optimizes energy distribution, controls weld pool dynamics, and manages thermal cycles. The study provides a foundational understanding and practical guidelines for deploying this efficient and capable welding technology in industrial applications requiring the joining of thick aluminum sections, offering a compelling alternative to multi-pass conventional techniques. Future work could explore the use of different shielding gas mixtures, the application to other aluminum alloy series, and the implementation of real-time adaptive control systems to further enhance process robustness..

References

[1] Wu, F., Flint, T. F., Falch, K. V., Smith, M. C., Drakopoulos, M., Mirihanage, W. Mapping flow evolution in gas tungsten arc weld pools [J]. International Journal of Heat and Mass Transfer, 2021, 179: 121679.

[2] Xu, B., Chen, S., Tashiro, S., Jiang, F., Tanaka, M. Physical mechanism of material flow in variable polarity plasma arc keyhole welding revealed by in situ x-ray imaging [J]. Physics of Fluids, 2021, 33: 017121-1–017121-10.

[3] Xu, B., Chen, S., Tashiro, S., Jiang, F., Nguyễn, V. A., Tanaka, M. Material flow analyses of high-efficiency joint process in VPPA keyhole flat welding by X-ray transmission system [J]. Journal of Cleaner Production, 2019, 250: 119450.

[4] Yang, T., Xiong, J., Chen, H. Effect of process parameters on tensile strength in plasma-MIG hybrid welding for 2219 aluminum alloy [J]. International Journal of Advanced Manufacturing Technology, 2015, 84(9–12): 2413–2421.

[5] Yang, T., Gao, H., Zhang, S., Wu, L. Interface behavior of copper and steel by plasma-MIG hybrid arc welding [J]. Acta Metallurgica Sinica (English Letters), 2013, 26(3): 328–332.

[6] You, D., Gao, X., Katayama, S. Monitoring of high-power laser welding using high-speed photographing and image processing [J]. Mechanical Systems and Signal Processing, 2014, 49(1–2): 39–52.

[7] Yang, T., Chen, L., Zhuang, Y., Liu, J. F., Chen, W. L. Arcs interaction mechanism in Plasma-MIG hybrid welding of 2219 aluminium alloy [J]. Journal of Manufacturing Processes, 2020, 56: 635–642.

[8] Brauers, J., Aach, T. Multispectral imaging with optical bandpass filters: tilt angle and position estimation [J]. Color Imaging XIV: Display, Processing, Hardcopy, and Applications, 2009, 7241: 72410Z.

[9] Bunaziv, I., Akselsen, O. M., Frostevarg, J., Kaplan, A. F. H. Deep penetration fiber laser-arc

ISSN 2616-5767 Vol.9, Issue 1: 40-46, DOI: 10.25236/AJETS.2026.090105

hybrid welding of thick HSLA steel [J]. Journal of Materials Processing Technology, 2018, 256: 216–228.

[10] Faraji, A. H., Goodarzi, M., Seyedein, S. H., Barbieri, G., Maletta, C. Numerical modeling of heat transfer and fluid flow in hybrid laser–TIG welding of aluminum alloy AA6082 [J]. International Journal of Advanced Manufacturing Technology, 2014, 77(9–12): 2067–2082.

[11] Guo, Y., Pan, H., Ren, L., Quan, G. An investigation on plasma-MIG hybrid welding of 5083 aluminum alloy [J]. International Journal of Advanced Manufacturing Technology, 2018, 98(5–8): 1433–1440.