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Hybrid laser-arc welding of low-alloy steels: From scientific concept to industrial technology (1970s–2020s)

Abstract. *The article examines the historical development of hybrid laser-arc welding of low-alloy steels from the formulation of the hybrid concept in the late 1970s to its emergence as an industrial technology in the early 21st century. Two interrelated but historically non-synchronous trajectories are identified: the evolution of fundamental and applied scientific research on laser-arc interaction and the subsequent formation of sustainable industrial applications in shipbuilding, pipeline welding, wind turbine tower manufacturing, and energy structures. Based on scientific publications, institutional reports, and documented industrial implementations in Germany, Denmark, Finland, USA and China, the path of hybrid welding transition from laboratory experiments to serial production in sectors with complex design requirements is reconstructed. Particular attention is paid to the role of leading research centers, as well as technology transfer processes. It is shown that the significant time lag between scientific justification and industrial implementation was due not only to the level of development of laser equipment, but also to institutional conservatism, certification barriers and high capital intensity of laser-oriented production systems. The sectoral nature of the technology's spread is separately analyzed, which explains why hybrid laser-arc welding first became established in European shipbuilding, later in selected pipeline projects in North America, then in the production of wind energy towers in Germany, and to the greatest extent in offshore and energy structures in China. The fundamentally important rethinking of this technology in the context of the United Nations Sustainable Development Goals is also considered, with an emphasis on reducing heat input, reducing welding consumables, reducing deformations and extending the service life of large steel structures. It is proven that hybrid laser-arc welding did not emerge as a universal alternative to* *traditional arc or submerged arc processes, but as a highly productive targeted solution determined by the interaction of scientific knowledge, industrial demand, institutional networks, and long-term structural changes in steel-intensive industries.*

Keywords: *hybrid laser-arc welding; low-alloy steels; history of welding technologies; laser materials processing; science-industry interaction; sustainable development*

Introduction.

Low-alloy steels have long been among the most widely used structural materials in heavy industry, transport, infrastructure and energy systems. Their widespread use stems from a balance of mechanical strength, weldability, cost-effectiveness, and material availability.

In the late 20th century, the growing scale and technical demands of welded steel structures (thicker plates, longer weld seams, higher production rates) highlighted the limitations of conventional arc-based welding. In particular, for thick-section joints, conventional arc welding often required multiple passes, produced wide heat-affected zones, and introduced significant distortion and residual stress (Lobanov, Poznyakov, Pivtorak, Mikhodui, & Orlovs'kyi, 2009; Paton, 2003; Poznyakov, Kasatkin, Zhdanov, & Strizhak, 2005). At the same time, the effort to use laser welding methods offered high energy density and deep penetration but encountered limitations related to joint fit-up tolerances, gap sensitivity, and cost of high-power laser equipment (Krivtsun & Seyffarth, 2002; Piekarska & Kubiak, 2013; Shelyagin et al., 2005b).

The concept of combining a laser beam with an electric arc, now known as hybrid laser-arc welding (HLAW), emerged in this context (Figure 1). According to technical histories, the first demonstrations of what later became called HLAW date to the late 1970s under the term "arc-augmented laser welding" (Eboo, Steen, & Clarke, 1978; Steen & Eboo, 1979; Steen, 1980).

Over the following decades, hybrid welding developed at the intersection of several disciplines: laser physics, arc plasma physics, metallurgical science, welding engineering, and later automation and control engineering. It was not a one-time invention but rather a slow convergence of multiple lines of research and development. By the 1990s, researchers in welding institutes and laser-technology centers began to treat HLAW as a distinct subject. In parallel, industrial demand (especially from sectors working with thick low-alloy steel plates, such as shipbuilding, pipelines, heavy machinery, railway manufacturing and energy) created pressure for a welding process combining depth, speed, and tolerance to joint imperfections.

Despite a growing technical literature (on thermal behaviour (Gu, Li, H., & Li, L. J., 2013;Piekarska & Kubiak, 2013; Wei, Li, Yang, Gao, & Ding, 2015), weld pool dynamics (Krivtsun, Reisgen, Semenov, & Zabirov, 2016; Üstündağ, Fritzsche, Avilov, Gumenyuk, & Rethmeier, 2018a; Yang et al., 2020), metallurgical effects (Berdnikova, Poznyakov, Bernatskyi, Alekseienko, & Sydorets, 2019; Bunaziv, Akselsen, Frostevarg, & Kaplan, 2018a; Górka & Stano, 2018), weld quality (Kim, Hirohata, & Inose, 2014; Liu et al., 2024; Norman, Karlsson, & Kaplan, 2011), process stability (Gu, Li, H., & Li, L. J., 2013; Liu et al., 2023; Moradi, Ghoreishi, Frostevarg, & Kaplan, 2013)) the historical development of hybrid laser-arc welding of low-alloy steels, considered as a coherent technological trajectory, has rarely been treated as an independent subject in history-of-technology or history-of-science studies. Most publications remain firmly within engineering and materials science disciplines, focusing on process parameters and mechanical outcomes, not on institutional developments, national research traditions, or the broader industrial and socio-economic context.

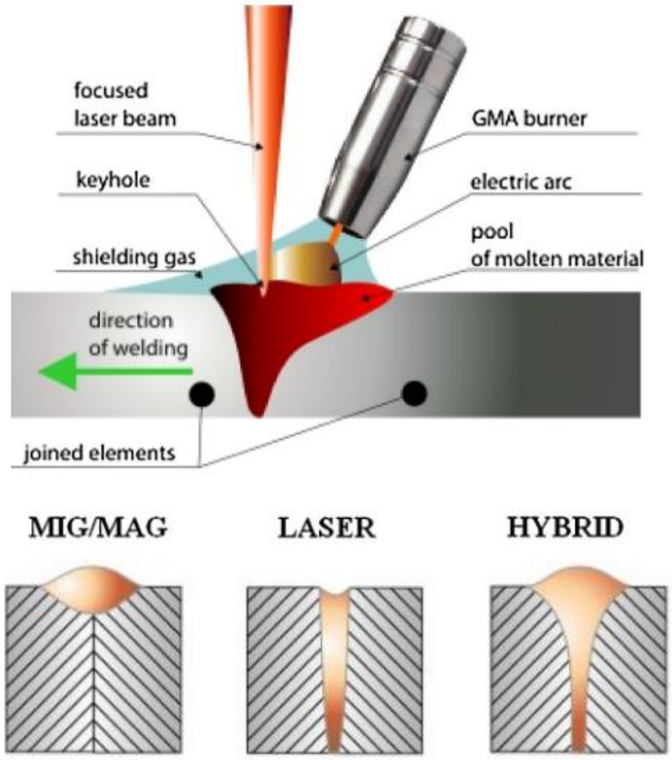

Figure 1. Scheme of hybrid laser arc welding process and patterns of formation of weld beads during arc welding, laser welding and hybrid laser arc welding (Acherjee, 2018a).

This article takes that broader historical view. It aims to reconstruct the evolution of HLAW for low-alloy steels, from its scientific origins to its industrial applications, with specific attention to dates, institutional actors, quantitative milestones where available, and the interplay between research, technology, and industrial demand. The article treats this evolution as a two-level process: first, the development of fundamental and applied research; second, the diffusion into stable industrial practice. It also considers the role of HLAW in longer-term trends in industrial modernization and sustainable use of steel structures.

Methodology.

This study applies a historical-analytical methodology combined with comparative and contextual analysis, which are often used in similar studies (Strelko, 2021; Strelko & Pylypchuk, 2021; Strelko, Pylypchuk, & Berdnychenko, 2019). The central task is to reconstruct the long-term formation of HLAW of low-alloy steels as a scientific field and as an industrial technology, with clear chronological markers and institutional attribution. The core empirical basis of the study consists of three major groups of sources.

First, peer-reviewed scientific literature on laser welding, arc welding, and hybrid processes published's between 1978 and 2025. The earliest technical descriptions of arc-assisted laser welding appear in the late 1970s, while systematic hybrid welding studies became visible in international journals from the early 1990s.

Second, international patent documentation on hybrid laser-arc welding systems and process control was examined. A targeted search of Espacenet and Google Patents for the period 1980–2025 yields more than 1,200 patent families directly related to hybrid laser-arc welding heads, laser-arc coupling methods, and adaptive control systems.

Third, reports and technical papers from major welding and laser research institutions were analyzed. These include publications from the Fraunhofer Institute for Laser Technology, RWTH Aachen University, Fraunhofer Institute for Production Systems and Design Techology and Federal Institute for Materials Research and Testing (Germany), Edison Welding Institute and Pennsylvania State University (USA), Osaka University (Japan), Harbin Institute of Technology and Tianjin University (China), Lappeenranta University of Technology and Aalto University (Finland), SINTEF and Norwegian University of Science and Technology (Norway), Luleå University of Technology (Sweden), Silesian University of Technology and the Welding Institute in Gliwice, Częstochowa University of Technology (Poland) and the E. O. Paton Electric Welding Institute (Ukraine).

The methodological separation between fundamental research, applied engineering research, and industrial implementation is a key principle of this study. Fundamental research includes laser-metal interaction physics, arc plasma behavior, and thermophysical modeling. Applied research includes hybrid process stability, metallurgical phase transformations in low-alloy steels, and weld quality optimization. Industrial implementation is traced through pilot plants, serial production lines, and certified welding procedures.

Comparative national analysis is used to identify differences in scientific traditions, industrial incentives, and technological policy. The study focuses primarily on Germany, the United States, Japan, China, and Eastern Europe, where continuous research trajectories in hybrid welding can be documented from the 1990s onward.

Finally, contextual interpretation is applied to relate hybrid laser-arc welding to broader processes of industrial modernization, energy efficiency, and sustainability.

This allows a historical connection to be drawn between welding technology development and long-term transformations of industrial production systems rather than treating HLAW solely as an isolated technical process.

Early Priority and the "First Publication" on Hybrid Welding.

The question of which work should be regarded as the "first" publication on hybrid laser-arc welding cannot be answered unambiguously, because different communities have fixed priority at different points in Steen's early work. Chronologically, the conference paper "Arc Augmented Laser Welding", presented at *the 4th International Conference on Advances in Welding Processes* in Harrogate in May 1978, is the earliest public description of a laser weld augmented by an electric arc (Eboo, Steen, & Clarke, 1978). Recent overview articles and handbooks explicitly treat this *Harrogate paper* as the initial disclosure of the hybrid concept and cite it as such when describing the late-1970s origins of hybrid welding.

In the welding-technology literature, however, the 1979 journal article by Steen and Eboo, "Arc Augmented Laser Welding", published in *Metal Construction*, is often treated as the first "real" hybrid welding publication (Steen & Eboo, 1979). Educational reviews and technical reports refer to this paper as the point at which hybrid welding was "originally invented" for combined laser-TIG welding, and European reviews on hybrid laser-arc processes routinely cite this 1979 article as the starting reference in their historical sections.

A third group of authors, especially in physics-oriented and numerical-simulation work, takes the 1980 article "Arc Augmented Laser Processing of Materials" in *Journal of Applied Physics* as the primary reference (Steen, 1980). In reviews of hybrid welding physics and numerical modelling, the hybrid concept is often said to have been "introduced around 1980" and directly linked to this paper, which formulates arc-augmented laser processing as a general materials-processing idea rather than as a specific welding procedure.

Thus, there is no single universally accepted "first" publication. In this article we therefore distinguish explicitly between three levels of priority: the 1978 *Harrogate conference paper* as the first public disclosure of hybrid welding, the 1979 *Metal Construction* article as the first archival welding-journal paper on the process, and the 1980 *Journal of Applied Physics* article as the first broad physical formulation of arc-augmented laser processing. This distinction helps to clarify the apparent confusion in the literature, where different authors label different members of this trio as the "first" depending on whether their focus is conference precedence, welding practice, or general process physics.

Results.

1. Periodization: Historical Development of Scientific Research (Fundamental and Applied).

The historical development of scientific research on hybrid laser-arc welding of low-alloy steels can be divided into four main stages. These stages reflect changes in laser technology, arc power sources, diagnostic tools, and computational modeling, as well as shifts in the balance between fundamental and applied research.

1.1. Stage I (1970s–1980s): Physical Foundations of Hybrid Interaction.

The first stage is associated with the formation of the physical foundations of laser-metal and arc-plasma interaction, prior to the establishment of hybrid welding as an independent applied field. During the 1970s, laser welding research was focused primarily on the keyhole mechanism, laser absorption in metals, and melt pool dynamics. Industrial CO_2 lasers with power levels of 1–3 kW became available by the mid-1970s, enabling systematic penetration studies in carbon and low-alloy steels with thicknesses up to 5–8 mm in a single pass.

During this first stage, research was focused less on specific industrial steels and more on understanding the basic mechanisms of interaction between the laser-induced keyhole, the arc plasma and the molten pool. Early experiments examined how arc polarity, current, and shielding gas composition affect the shape and stability of the keyhole, the absorption of laser radiation, and the distribution of heat input in the joint. The central questions were whether the arc could increase effective energy coupling into the material, stabilize the keyhole against collapse, and extend the permissible range of joint fit-up and surface conditions compared with pure laser welding.

In parallel, the first analytical and semi-empirical models of hybrid interaction began to appear. Researchers attempted to describe the temperature field, the shape of the molten pool, and the vapor-plasma plume when an arc is present above the laser spot. These models were still simplified, but they introduced a conceptual framework that distinguished hybrid processes from both conventional arc welding and classical laser welding. By the end of the 1980s, the main physical features of arc-augmented laser processing had been identified: the possibility of deeper penetration at a given total power, the redistribution of heat between the arc and the laser, and a potential increase in process robustness. At the same time, this work remained predominantly experimental and conceptual.

1.2. Stage II (Early–Mid 1990s): Formation of Hybrid Welding as an Applied Research Field.

The second stage begins in the early 1990s, when laser technology, numerical control systems, and arc power sources reached a level that allowed synchronized hybrid operation to be studied systematically. During this decade, continuous-wave lasers with power levels of 3–6 kW became increasingly available to research laboratories and industrial development centers. By the end of the 1990s, experimental hybrid welding of low-alloy steels with thicknesses of 8–12 mm in a single pass had already been repeatedly demonstrated in laboratory settings.

During this period, the first numerical models of hybrid heat sources also appeared, combining Gaussian laser distributions with distributed arc heat input. These models represented a methodological shift from descriptive experimentation toward predictive simulation.

1.3. Stage III (2000s): Expansion of Applied Metallurgical and Process Control Research.

The 2000s represent a phase of rapid expansion of applied scientific research. Several structural factors contributed to this acceleration. First, industrial fiber and disk lasers with power levels exceeding 8–10 kW became commercially available after approximately 2005–2010, significantly improving efficiency and beam quality. Second, real-time vision systems and digital synchronization tools enabled precise coordination of laser and arc heat sources.

During this decade, hybrid welding research focused on: thermal field distribution; weld pool hydrodynamics; phase transformations in low-alloy steels; defect formation mechanisms (porosity, hot cracking); mechanical performance of hybrid welds under static and cyclic loading.

By the late 2000s, hybrid welding was no longer regarded as an exotic process. Scientific publications documented stable welding of low-alloy steels with thicknesses of 12–20 mm in a single pass, with welding speeds exceeding those of multi-pass arc welding by factors of 2–4.

1.4. Stage IV (2010s–2020s): Digitalization, Fiber Lasers, and Process Optimization.

The most recent stage, beginning in the early 2010s, is characterized by the integration of digital monitoring, computational control, and artificial intelligence methods into hybrid welding systems. Fiber lasers with output powers of 15–30 kW became industrially widespread after 2012–2017, enabling single-pass welding of steel plates exceeding 20–25 mm thickness under controlled conditions.

Research during this period increasingly focused on: real-time process monitoring using high-speed cameras and optical sensors; adaptive control of laser-arc coupling; numerical “digital twin” models of hybrid weld pools; residual stress minimization and fatigue-life prediction.

At this stage, fundamental plasma–laser interaction studies became tightly integrated with industrially oriented optimization. The boundary between fundamental and applied research became increasingly blurred, reflecting the maturity of hybrid laser-arc welding as a scientific and technological field.

2. Leading Countries and Scientific Centers.

The development of hybrid laser-arc welding of low-alloy steels has been shaped by a relatively small group of countries with strong welding science, advanced laser technology, and intensive industrial use of thick steel structures. Their leading role is visible in three dimensions: early entry into hybrid research, systematic work on thick low-alloy steels, and documented transfer of hybrid technologies into shipbuilding, pipelines, heavy machinery, rail, and energy infrastructure.

2.1. Germany: Fraunhofer ILT, RWTH, Fraunhofer IPK, BAM and the Engineering of Hybrid Laser–Arc Welding for Thick Steels.

Germany occupies a central position in the historical development of hybrid laser-arc welding, particularly in relation to thick-section and high-strength structural steels. From the late 1990s onward, German research institutions played a decisive role in transforming hybrid welding from a laboratory concept into a robust engineering process suitable for heavy steel fabrication. Among these institutions, the Fraunhofer Institute for Laser Technology (Fraunhofer ILT) in Aachen emerged as one of the most influential centers for applied hybrid welding research.

At the turn of the millennium, researchers at Fraunhofer ILT introduced one of the most consequential technical innovations in the field: the integrated hybrid welding head, often referred to as the “integrated nozzle”, which combined laser optics and a MAG welding torch into a single system (Figure 2).

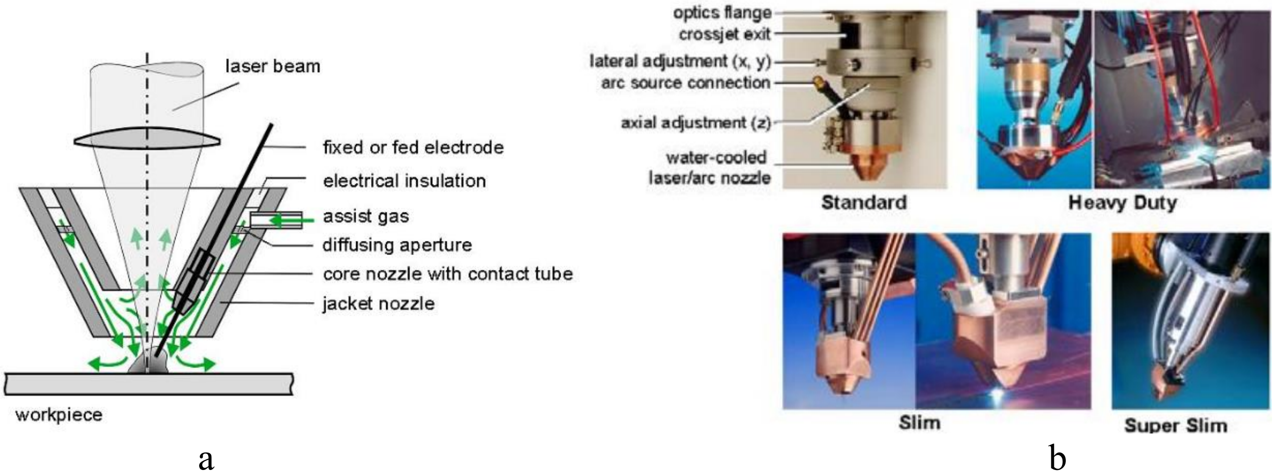

Figure 2. Integrated hybrid welding nozzle: *(a)* principle of the integrated hybrid welding nozzle; *(b)* standard and customized hybridwelding heads with the integrated nozzle design (Petring & Fuhrman, 2004).

This design significantly improved process stability and industrial usability. In a series of papers presented at ICALEO and related conferences (Petring, Fuhrmann, Wolf, & Poprawe, 2003; Petring & Fuhrmann, 2004; Petring, Fuhrmann, Wolf, & Poprawe, 2007). Dirk Petring and co-authors documented industrial applications of this concept beginning around 2000, including hybrid laser-MAG welding of structural and low-alloy steels with thicknesses of approximately 20–30 mm in single- or double-sided configurations. These studies are notable because they go beyond penetration depth and welding speed, reporting also on weld quality, defect sensitivity, and fatigue performance in steels used for tanks, ship structures, and heavy machinery.

Fraunhofer ILT's contribution was not limited to hardware development. Throughout the 2000s and early 2010s, ILT researchers conducted systematic investigations into process windows for hybrid laser-MAG welding of steels, addressing joint preparation, laser-arc positioning, filler wire selection, and shielding gas composition. These studies established quantitative tolerances for gap width and misalignment and clarified how hybrid welding parameters influence weld bead geometry and microstructural evolution in low-alloy steels. Results were published in international journals and proceedings and formed the technical basis for transferring hybrid welding into shipbuilding and heavy-structure production (Kaierle, Bongard, Dahmen, & Poprawe, 2000; Petring, 2013; Webster, Kristensen, & Petring, 2008).

Parallel to the work at ILT, German university groups (particularly at RWTH Aachen University) contributed numerical modeling and advanced diagnostics (Olschok, Reisgen, & Dilthey, 2007; Reisgen, Olschok, Jakobs, & Engels, 2016; Wieschemann, Kelle, & Dilthey, 2003). Their studies addressed heat source interaction, molten pool dynamics, and solidification behavior in laser-MAG hybrid welding of steels, linking process parameters with microstructure and mechanical properties. This modeling work complemented ILT's applied research by providing mechanistic explanations for observed stability limits and defect formation, thereby refining process design for low-alloy structural steels.

In the 2010s, hybrid laser-arc welding of thick steels became part of a broader German research agenda focused on energy infrastructure and large welded components. A representative example is the works of Fraunhofer Institute for Production Systems and Design Techology (Fraunhofer IPK in German) and Federal Institute for Materials Research and Testing (BAM in German) in Berlin. These research extended the German thick-steel agenda by focusing on electromagnetic support of the weld pool in hybrid laser-arc welding (Üstündag, Avilov, Gumenyuk, & Rethmeier, 2018; Üstündağ, Fritzsche, Avilov, Gumenyuk, & Rethmeier, 2018a, 2018b). A series of studies demonstrated that applying an oscillating magnetic field beneath the joint can suppress root sagging and enable single-pass welding of ferromagnetic steels up to approximately 28 mm in thickness, while maintaining acceptable mechanical properties. These concepts were subsequently applied to wind-tower fabrication and energy-transition structures, where BAM and associated projects proposed hybrid laser-arc welding as an alternative to multi-layer submerged arc welding for circumferential welds in 20–30 mm thick tower shells (Brunner-Schwer, Üstündağ, Bakir, Gumenyuk, & Rethmeier, 2023). This work reflects a shift from experimental feasibility toward system-level production strategies for large cylindrical steel structures.

BAM also became a central actor in pipeline-oriented hybrid welding, often in close cooperation with Fraunhofer IPK. Studies (Gook, Gumenyuk, & Rethmeier, 2014; Üstündağ, Gook, Gumenyuk, & Rethmeier, 2020) examined hybrid welding of high-strength pipeline steels such as X80 and X120, including orbital hybrid welding of large-diameter pipes. These works defined realistic process windows in terms of welding speed, penetration, and defect control and are now widely cited in reviews and design recommendations for hybrid welding of linepipe steels.

Taken together, German research on hybrid laser-arc welding of low-alloy steels is characterized by the integration of equipment development (Fraunhofer ILT), process modeling (RWTH), materials performance assessment (BAM, Fraunhofer IPK), and sector-specific application (shipbuilding, energy, pipelines, offshore structures). This multi-institutional framework has made Germany one of the key reference points for hybrid welding of thick structural steels and has strongly influenced both European and global development trajectories in this field.

2.2. United States: DebRoy's Group and the Pipeline-Structure Focus.

In the United States, leadership in hybrid laser-arc welding is shared between academic groups (DebRoy's and others) and the Edison Welding Institute (EWI).

The applied pillar is EWI. From the early 2000s, EWI worked on hybrid laser-arc welding for pipelines and structural components under sponsorship from US regulators and industry (Harris & Norfolk, 2008; Victor, Nagy, Ream, & Farson, 2009; Victor, 2011). EWI and associated studies focused on transition from laboratory demonstrations to field-suitable procedures, including discussions of weld procedure qualification, toughness requirements, and defect acceptance criteria. These efforts helped define the place of hybrid welding within North American pipeline and structural standards.

Researchers from Tarasankar DebRoy's group (Pennsylvania State University) are often cited in hybrid laser-arc welding because they treated the process as a coupled heat transfer + fluid flow + arc/plasma interaction problem, and then used that framework to explain the practical behavior that production engineers care about (penetration, pool shape, gap tolerance, and stability). A key example is Ribic, Rai and DebRoy's paper (2008) on GTA/laser hybrid welding, which combines modeling with experimental comparison and shows (among other points) that hybrid welding can broaden the weld pool and improve gap-bridging relative to laser-only welding, and that penetration can peak at an optimal separation distance between the laser beam and arc electrode. Although the paper is not restricted to a single low-alloy grade, it is widely used as a foundational reference for hybrid welding of structural steels because the governing mechanisms (convection forces, heat-source coupling, pool geometry control) carry directly into low-alloy steel procedure development.

In parallel, DebRoy's group produced one of the most cited "map" papers in the field (Ribic, Palmer, & DebRoy, 2009). This article is commonly used as a starting point because it organizes the field around recurring technical barriers (process stability, defect mechanisms, and transferability of parameters) rather than presenting a single application case. They also pushed into diagnostics, for example by applying optical emission spectroscopy to hybrid welding plasmas and showing how arc current and heat-source separation influence measurable plasma properties that correlate with weld quality and stability (Ribic, Burgardt, & DebRoy, 2011).

U.S. contributions to hybrid laser-arc welding of low-alloy steels are distinguished by the tight coupling between scientific modeling and industrial qualification. University-based research, particularly from DebRoy's group, supplied a rigorous physical and numerical understanding of hybrid interaction, while EWI translated these insights into procedures suitable for pipelines and heavy structural components operating under strict regulatory constraints. This dual structure has shaped a distinctly American trajectory for hybrid welding research, in which the technology is evaluated primarily through its ability to meet qualification standards and service requirements in large-scale steel infrastructure.

2.3. Japan: Osaka University and High-Strength Bridge and Ship Steels.

Japan's contribution to the development of hybrid laser-arc welding is closely connected with national requirements in bridge construction, shipbuilding, and the fabrication of large steel structures, where low-alloy and high-strength steels are extensively employed. One of the most prominent research centers in this field is the Joining and Welding Research Institute (JWRI) of Osaka University, which has long combined experimental welding research with process modelling and structural performance evaluation. Earlier JWRI work from the 2000s and early 2010s concentrated on hybrid laser-MAG welding of structural steels with thicknesses of approximately 10–24 mm, using high-power disk or fiber lasers (Ohnishi, Kawahito, Mizutani, & Katayama, 2013; Pan, Mizutani, Kawahito, & Katayama, 2015; Pan, Mizutani, Kawahito, & Katayama, 2016). These studies examined penetration mechanisms, weld bead geometry, and porosity formation, often in connection with the weldability of high-tensile steels for shipbuilding and offshore structures. Productivity improvement and distortion reduction were recurrent themes, reflecting the needs of Japanese shipyards and heavy-fabrication industries.

Japanese researchers have also made contributions to the physical modelling of hybrid heat sources and to the analysis of arc behavior under hybrid conditions (Chen, et al., 2023; Kim, Hirohata, & Inose, 2014; Hirohata et al., 2019). Experimental and numerical studies have quantified changes in arc characteristics, metal transfer modes, and molten pool dynamics when an arc operates in the presence of a laser beam. Such work has clarified how the interaction between laser radiation and arc plasma affects penetration efficiency and melting behavior in steels, providing a scientific basis for process optimization.

Japanese contributions to hybrid laser-arc welding research demonstrate a consistent coupling between fundamental process understanding and application-oriented studies tailored to bridges, ships, and high-strength structural steel fabrication.

This alignment between scientific analysis and national infrastructure needs has been a defining feature of Japan's role in the historical development of hybrid welding technologies.

2.4. China: Harbin, Tianjin and the Rapid Expansion of Hybrid Laser-Arc Welding Research.

Over the past two decades, China has emerged as one of the most active centers of research on hybrid laser-arc welding, including extensive work on low-alloy and structural steels used in shipbuilding, pipelines, offshore platforms, and energy infrastructure. This rapid expansion reflects both the scale of domestic demand for steel-intensive structures and sustained investment in laser manufacturing and welding research. As a result, Chinese research in this field spans fundamental studies of laser-arc interaction, applied investigations of joint performance, and large-scale industrial implementation.

A central role in fundamental research belongs to the State Key Laboratory of Advanced Welding and Joining at Harbin Institute of Technology. Numerous studies from this laboratory address weld pool dynamics, keyhole stability, and defect formation in hybrid laser-arc welding of steels. Experimental and numerical work has examined arc characteristics, metal transfer behavior, and their combined influence on penetration depth and weld bead geometry in thick steel plates (Liu et al., 2020; Yang et al., 2020; Zhenglong, Caiwang, Yanbin, & Zhongshao, 2013). These studies have clarified how the arc modifies laser energy absorption and molten pool flow, providing a physical basis for improving process stability and reducing defects such as porosity and lack of fusion.

Another important academic center is Tianjin University. Research conducted there has focused on laser and laser-arc hybrid welding of steels and other structural alloys, with strong emphasis on numerical modelling and process control (Gu, Li, H., & Li, L. J., 2013; Wei, Li, Yang, Gao, & Ding, 2015; Wu, Luo, & Ao, 2023). Tianjin-based studies have developed coupled thermal-fluid models to describe heat source interaction, molten pool behavior, and solidification dynamics under hybrid conditions. These models are frequently validated against experimental welds in low-alloy steels and are intended to support transfer of hybrid welding to complex structural applications.

Beyond laboratory-scale studies, Chinese publications and technical reports increasingly document industrial-scale integration of high-power hybrid laser-arc welding systems (Liu et al., 2024; Zhang, Li, Gao, & Zeng, 2017; Zhang et al., 2023). Examples include hybrid welding of thick steel plates for offshore wind towers, ship hull structures, and heavy components for energy infrastructure. These implementations demonstrate a level of scale that remains uncommon in many other countries and is facilitated by the availability of domestically produced high-power fiber and disk lasers.

The breadth of Chinese activity is reflected in recent international reviews (Ma, Cheng, Ning, Zhang, & Na, 2021; Liu et al., 2023; Liu et al., 2024). In particular, the comprehensive review by He et al. (2025) in *Metals* summarizes global progress in laser-arc hybrid welding and highlights the high volume of Chinese publications and projects. The review identifies joint design, microstructure evolution, mechanical property evaluation, and laser-arc interaction mechanisms in steels as key ongoing research directions in China, and emphasizes the strong linkage between academic research and industrial deployment.

Chinese research on hybrid laser-arc welding of low-alloy steels is characterized by the close coupling of fundamental process studies, numerical modelling, and large-scale industrial application. This combination, supported by strong domestic demand and advanced laser manufacturing capabilities, positions China as one of the principal drivers of current and future developments in hybrid welding technologies for structural steels.

2.5. Northern and Eastern Europe: Finland, Norway, Sweden and Poland.

Northern and Eastern Europe have also contributed significantly to hybrid welding research, particularly through high-quality reviews and detailed process investigations.

Research on hybrid laser-arc welding of low-alloy and structural steels in Finland has developed along two closely connected but methodologically distinct lines. The first is associated with process-parameterization and process-physics studies carried out at Lappeenranta University of Technology (now LUT University). The second line is linked to application-oriented investigations focused on shipbuilding and structural integrity, conducted within VTT and the ship mechanics community of Helsinki University of Technology (later Aalto University).

Representative of the LUT approach is the study by Kah, Salminen, and Martikainen on the role of shielding gases in hybrid laser-arc welding of steels, which treats gas composition as a primary control variable influencing plasma behavior, process stability, penetration depth, and the reproducibility of welding procedures. Their work (Kah, Salminen & Martikainen, 2011), is significant because it contributed to transforming hybrid laser-arc welding from an experimental combination of heat sources into a process that can be systematically parameterized and transferred to industrial practice. Rather than presenting isolated demonstration welds, this line of research emphasizes conditions and boundaries directly relevant to procedure development for structural steels.

More application-oriented Finnish studies addressed hybrid welding in the context of real ship structures at an early stage. A widely cited example is the work by Jokinen, Vihervä, Riikonen, and Kujanpää (2000) on hybrid Nd:YAG laser-GMAW welding of ship structural steel A36. This study reports butt-joint trials under shipbuilding-relevant conditions, including gap tolerance, macrostructural features, and hardness distributions, situating the results explicitly within a framing and fabrication context. The article provides experimental data and weld quality assessments that are directly comparable to conventional techniques.

A related but distinct contribution emerged from the mechanics and fatigue research tradition at Aalto University, represented by the work of Remes and Värstä (2010). Their study on weld geometry variability in laser-hybrid butt joints, examines how geometric scatter affects notch stresses and fatigue-life prediction, an issue of particular importance when hybrid welding is incorporated into classification rules and design standards for structural steels.

Finnish contributions form an important link between process definition and structural performance assessment: LUT-based research primarily formalizes how hybrid welding processes should be executed, while VTT- and Aalto-linked studies address how the resulting joints should be evaluated when applied to ships and other long-life steel structures.

Norwegian research on hybrid laser-arc welding of low-alloy and structural steels is closely associated with SINTEF and Norwegian University of Science and Technology and is characterized by a strong focus on thick-section steels and offshore-related applications. Within this research landscape, the works of Ivan Bunaziv and his colleagues occupies a central position, as it consistently addresses industrially relevant questions such as achievable penetration depth, process efficiency, defect formation, and mechanical performance under demanding service conditions (Bunaziv, Akselsen, Frostevarg, & Kaplan, 2018a; Bunaziv, Akselsen, Frostevarg, & Kaplan, 2018b Bunaziv, Akselsen, Frostevarg, & Kaplan, 2020; Bunaziv, Ren, & Olden, 2023).

One of the most frequently cited contributions is the study on deep-penetration fiber laser-arc hybrid welding of thick HSLA steel (Bunaziv, Akselsen, Frostevarg, & Kaplan, 2018a). This paper systematically analyzes penetration behavior, process stability, and weld quality for thick plates, providing quantitative guidance for parameter selection rather than isolated demonstration results. Closely related work on the penetration efficiency of thick plate hybrid welding (Bunaziv, Akselsen, Frostevarg, & Kaplan, 2018b), examines the influence of joint preparation and process variables on effective penetration, which is critical for reducing the number of welding passes in heavy fabrication.

Subsequent studies extended this approach to application-specific contexts. In 2019, Bunaziv and co-authors investigated hybrid laser-arc welding of steels intended for low-temperature service (Bunaziv, Akselsen, Frostevarg, & Kaplan, 2019), linking welding parameters to toughness and suitability for shipbuilding and offshore structures operating in cold environments. Later work addressed single-pass hybrid welding of 12–15 mm structural steel, focusing on process stability and typical imperfections relevant to industrial production (Bunaziv, Akselsen, Frostevarg, & Kaplan, 2020).

Norwegian contributions frame hybrid laser-arc welding as a realistic alternative to multi-pass arc welding for thick structural steels, provided that process windows are rigorously defined and quality-limiting defects are well understood. This combination of experimental depth and application relevance explains the prominent position of Norwegian research in the international literature on hybrid welding of low-alloy steels.

Swedish research on hybrid laser-arc welding of low-alloy and structural steels is strongly associated with Luleå University of Technology, especially the long-running line led by Alexander Kaplan. A recurring theme in this body of work is that the key barrier to industrial transfer is not penetration alone but repeatable process stability at production speeds, particularly the control of surface shape and defects that become critical in structural steel fabrication. That emphasis is clear in the parameter-guideline paper by Eriksson, Powell, and Kaplan (2013), which explicitly aims to turn hybrid welding into usable rules for setup and operation rather than case-by-case trials. It is also visible in the stability study by Moradi, Ghoreishi, Frostevarg, and Kaplan (2013), which treats the hybrid process as a coupled system where stability depends on how laser-arc interaction affects transfer behavior and weld-surface dynamics.

A second distinct Swedish contribution is Luleå University of Technology’s detailed work on undercut formation and suppression, which matters in structural steels because undercuts are treated as imperfections with direct fatigue implications and often become limiting acceptance criteria. This mechanism-based approach is illustrated by Norman, Karlsson, and Kaplan (2011), who analyzed how undercuts form during laser hybrid arc welding and linked the phenomenon to surface condition and melt-flow behavior. Building on this, Frostevarg and Kaplan published an extensive classification and mapping of undercut types in laser-arc hybrid welding, including practical guidance on how positioning and melt-flow “tailoring” can extend the critical welding speed without undercuts (Frostevarg & Kaplan, 2014).

Together, these Swedish contributions are useful historically because they reflect a mature phase of the field: hybrid laser-arc welding is treated less as a novel combination of heat sources and more as a production process whose industrial value depends on defect mechanisms, stability margins, and parameter rules that can be transferred across shops and steel grades.

Research on hybrid laser-arc welding of low-alloy and structural steels in Poland has been concentrated primarily within the scientific and industrial network formed around Gliwice, notably the Silesian University of Technology and the Welding Institute in Gliwice. A representative example of this line of work is the study by Górka and Stano, which investigates hybrid laser-MAG welding of TMCP S700MC steel with a thickness of 10 mm (2018). This paper analyzes weld microstructure and mechanical properties and explicitly positions hybrid welding as a technologically viable method for joining high-strength structural steels used in load-bearing applications.

Closely related research addresses even higher-strength grades, such as S960QL, which are relevant for crane structures and other heavy-duty components. For instance, Urbańczyk and Adamiec report on hybrid laser-MAG welding of S960QL steel (5–7 mm), linking process parameters to resulting microstructures and mechanical performance in Materials (2021). This work reflects a broader Polish research focus on transferring hybrid welding procedures to steels with limited weldability margins.

Complementary procedure-oriented studies from the Welding Institute in Gliwice, published in the Bulletin of the Institute of Welding, further illustrate how hybrid laser-arc welding parameters are adapted for industrial practice, particularly for high-strength structural steels (Urbańczyk, Banasik, Stano, & Adamiec, 2018).

Alongside this application-driven strand, Polish researchers have also contributed significantly to the modelling and analytical description of hybrid welding processes. Work associated with Częstochowa University of Technology, such as the study by Piekarska and Kubiak, compares thermal phenomena in laser welding and laser-arc hybrid welding of S355 structural steel sheets using numerical modelling (Piekarska & Kubiak, 2013). This paper provides insight into heat-flow redistribution and thermal-cycle modification introduced by the arc component, offering a transferable framework for process optimisation across different steel grades.

Taken together, Polish contributions form a coherent body of work that combines experimentally validated procedures for high- and ultra-high-strength structural steels with modelling approaches that link process parameters to thermal and mechanical outcomes.

2.6. The Kyiv School of Hybrid Laser-arc Welding of Steels.

The development of HLAW of low-alloy and high-strength steels is closely tied to the E. O. Paton Electric Welding Institute (PWI) of the National Academy of Sciences of Ukraine in Kyiv. Since the late Soviet period, PWI has been the main national center for welding science, with a large staff and a clear focus on new process combinations for structural steels. In Ukraine and the broader Eastern European context, the PWI remains a reference institution. Historically, Paton’s work focused on arc (Paton, 2003; Paton, Akhonin, Prilutsky, 2011), electron beam (Paton et al., 2004; Paton et al., 2019) and electroslag welding (Paton, 1980), but in the 2000s, Paton-related publications also began to address laser and hybrid laser-arc processes (Krivtsun, 2001; Paton, Gvozdetskij, Krivtsun, & Zagrebel'nyj, Shulym, Dzheppa, 2002; Shelyagin et al., 2005a, 2005b).

Under Borys Paton’s leadership, the institute systematically explored the combination of laser radiation with electric arcs and plasma sources, extending earlier ideas proposed by W. M. Steen and others into industrially oriented hybrid processes. In this context, a group of researchers that we can call the “Kyiv School” formed around several key figures: Ihor Krivtsun, Volodymyr Shelyagin, Vladyslav Khaskin, Valeriy Poznyakov, Volodymyr Korzhyk, Volodymyr Sydorets, Liudmyla Markashova, Olena Berdnikova and their colleagues.

A first line of work is linked to Ihor Krivtsun, who played an important role in formalizing laser-arc and laser-plasma hybrid processes (Krivtsun, 2001). Together with German colleague Peter Seyffarth he co-authored the monograph *Laser-Arc Processes and Their Applications in Welding and Material Treatment* (2002), which systematized laser-arc interactions, energy balance and process windows for hybrid applications, including steels. In parallel, Krivtsun and co-authors published a number of articles on laser-arc and laser-microplasma welding (Paton, Gvozdetskij, Krivtsun, & Zagrebel'nyj, Shulym, Dzheppa, 2002). His group's theoretical and experimental work is repeatedly cited in later reviews on hybrid laser-plasma welding as providing the basic understanding of synergic effects and energy efficiency.

A second, an important contribution to the development of hybrid laser-arc welding of low-alloy steels has also been made by the group led by Volodymyr Shelyagin. While much of the Kyiv school's work is widely known for fundamental welding science, Shelyagin's group played a distinctive role in advancing process-oriented and equipment-focused studies aimed at practical hybrid welding applications. Their research by Volodymyr Shelyagin, Vladyslav Khaskin and their co-authors addressed the integration of laser and arc heat sources, stability of hybrid processes, control of weld formation, and adaptation of hybrid technologies to structural and pipeline steels under industrial conditions (Shelyagin et al., 2005a, 2005b, 2018). A characteristic feature of this work is its close coupling of experimental welding trials with the development of specialized technological solutions, including welding heads, process layouts, and control strategies suited to hybrid operation.

A third, very extensive line of research is associated with Valeriy Poznyakov and his colleagues, who focused on the weldability, structure and service properties of welded joints in low-alloy and high-strength steels. Since the mid-2000s, Poznyakov's group has published a series of studies on structural steels with yield strengths from 350 to 490 MPa and higher, used in bridges, storage tanks, stadium roofs and other large structures (Poznyakov, Kasatkin, Zhdanov, & Strizhak, 2005). From about 2015, part of this work shifted specifically to hybrid laser-arc welding of high-strength steel's 14KhGN2MDAFB and N-A-XTRA-70 (Berdnikova, Pozniakov, & Bushma, 2016; Poznyakov, Markashova, Berdnikova, Alekseienko, & Zhdanov, 2018; Poznyakov et al., 2019). Poznyakov and co-authors analyzed the structure and crack resistance of hybrid-welded high-strength steel's joints, showing that, with proper thermal cycles, the critical stress intensity factor approaches that of base metal. It showed that, under selected HLAW regimes, the impact toughness of the heat-affected zone and weld metal can reach levels sufficient for heavy-duty service, while also reducing joint width and heat input. An important feature of the Kyiv School is the close link between process development and detailed microstructural analysis (Berdnikova, Poznyakov, Bernatskyi, Alekseienko, & Sydorets, 2019; Markashova, Berdnikova, Alekseienko, Bernatskyi, & Sydorets, 2019; Berdnikova et al., 2020).

A fourthly line is associated with Volodymyr Korzhyk, Vladyslav Khaskin and their co-authors developed a separate but related direction: hybrid laser-plasma welding of steels and other alloys. A 2017 conference paper by Korzhyk and co-authors presented a brief retrospective of hybrid laser-plasma welding, formulated key objectives for the process and analyzed its industrial prospects (Korzhyk, Bushma, Khaskin, Dong, & Sydorets, 2017). In 2024, Korzhyk and co-authors published a comprehensive review, introducing quantitative criteria for the synergic effect and reporting process efficiencies in the range 1.5–2.4 for steels (Korzhyk et al., 2024). This work also described a coaxial head for laser-plasma welding developed at PWI, designed to reduce laser power requirements and relax edge-preparation tolerances in welding of thin-walled steel products such as pipes and profiles (Figure 3).

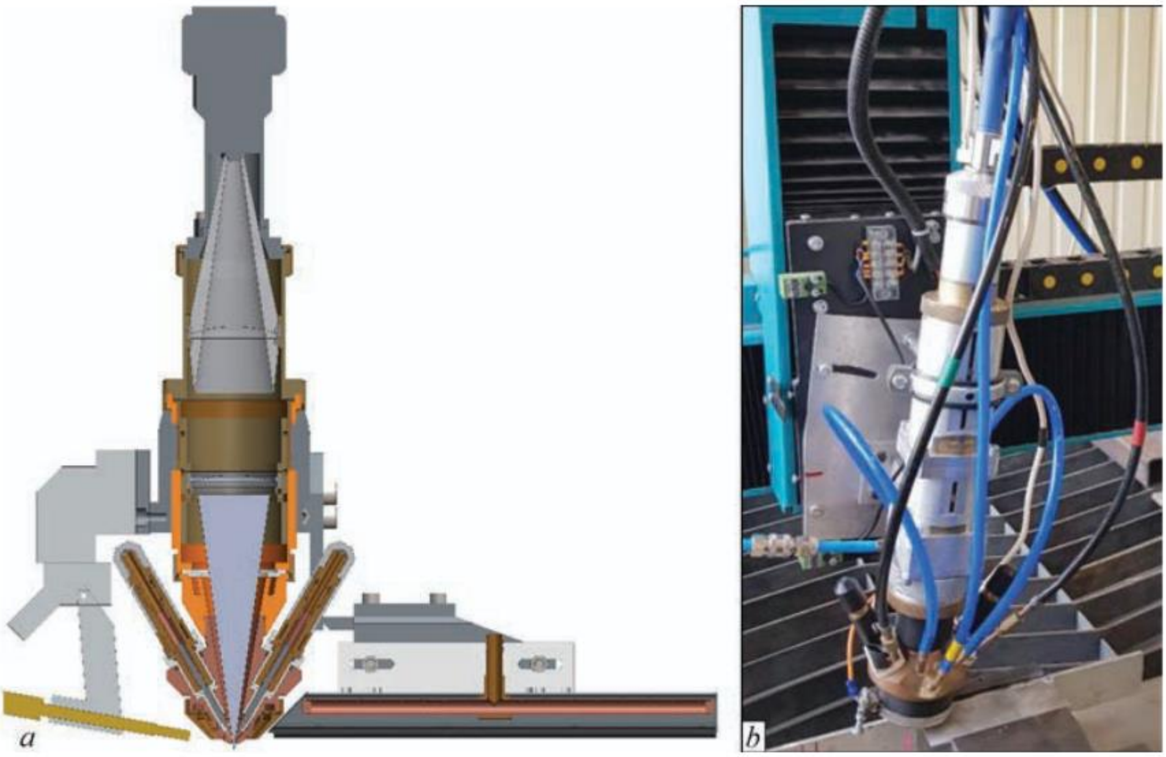

Figure 3. 3D-model *(a)* and appearance *(b)* of the head for laser and laser-plasma welding, developed at PWI (Korzhyk et al., 2024).

Taken together, the work of Paton, Krivtsun, Shelyagin, Khaskin, Poznyakov, Korzhyk, Sydorets, Markashova, Berdnikova and their colleagues forms a coherent Kyiv School of hybrid welding. It combines process physics, power-source engineering, detailed metallography and long-term service considerations, and it is embedded in international networks, especially with partners in China, Germany (Krivtsun, Reisgen, Semenov, & Zabirov, 2016; Reisgen, Krivtsun, Gerhards, &

Zabirov, 2016; Reisgen, Zabirov, Krivtsun, Demchenko, & Krikent, 2015) and other European countries. For the purposes of this article, this school can be seen as one of the central actors in the global historical development of hybrid laser-arc and related hybrid laser–plasma welding of low-alloy and high-strength steels.

3. Main Scientific Directions in Hybrid Welding of Low-Alloy Steels.

From the moment hybrid laser-arc welding moved beyond proof-of-concept experiments in the early 1990s, research on low-alloy steels developed along several stable scientific directions. These directions reflect the internal logic of the process itself: the interaction of two heat sources, the behavior of the molten pool, metallurgical transformations in the steel, and the formation of defects and mechanical properties. By the late 2000s, these directions had largely stabilized and continue to structure hybrid welding research today.

One of the earliest and most persistent research directions concerns the thermal field and hybrid heat-source modeling. In the 1990s, numerical descriptions of hybrid welding were still rudimentary and typically combined a Gaussian laser heat source with a distributed arc heat input. These early models were developed to explain why hybrid welding produces deeper penetration at comparable or even lower total heat input than pure arc welding. By the early 2000s, three-dimensional transient models were already being used to predict melt pool shape and cooling rates for laser-arc hybrid welding of carbon and low-alloy steels (Krivtsun, 2001; Krivtsun & Seyffarth, 2002; Ribic, Rai, & DebRoy, 2008).

A key methodological synthesis of hybrid heat-source modeling and fluid-flow behavior is given in the review by Ribic, Palmer and DebRoy (2009), which summarized how laser power, arc current, torch-beam distance and travel speed control penetration depth, weld width and thermal gradients in steels.

Subsequent computational studies in the 2010s introduced fully coupled thermal–fluid models that included Marangoni flow, electromagnetic stirring by the arc, and vaporization recoil pressure from the laser keyhole (Krivtsun, Reisgen, Semenov, & Zabirov, 2016; Piekarska & Kubiak, 2013; Ribic, Burgardt, & DebRoy, 2011). These models showed that in low-alloy steels the hybrid weld pool is dominated by forced convection rather than pure thermal diffusion, which explains the deeper and narrower penetration profile compared to arc welding.

A second major research direction concerns weld pool dynamics and arc-laser interaction mechanisms. Experimental high-speed imaging work carried out in the 2000s and 2010s, especially in China, Germany, Sweden and Ukraine, demonstrated that the arc plays a stabilizing role for the laser keyhole by preheating the steel surface and reducing reflectivity (Eriksson, Powell, & Kaplan, 2013; Gu, X. Y., Li, H., & Li, L. J. 2013; Reisgen, Zabirov, Krivtsun, Demchenko, & Krikent, 2015). Conversely, the laser acts as a constrictor of the arc column. Studies from the Tianjin University and Luleå University of Technology quantified oscillation frequencies of the molten pool and showed that hybrid interaction suppresses irregular droplet transfer typical for conventional MAG welding of low-alloy steels.

Closely connected to weld pool dynamics is the research direction devoted to defect formation mechanisms, especially porosity, lack of fusion and hot cracking. For low-alloy steels, porosity became a key issue in the early industrial adoption phase, particularly in the 2000s. It was shown that hydrogen content, laser-induced metal vapor, and unstable keyhole behavior were the main contributors (Petring & Fuhrmann, 2004; Shelyagin et al., 2005a; Victor, Nagy, Ream, & Farson, 2009). Studies demonstrated that adjusting the arc mode (pulsed MAG, CMT variants) and the laser-arc distance could significantly reduce pore density. By the late 2000s, stable pore-free hybrid welds in 12–20 mm thick low-alloy steels were already reported under laboratory and pilot-industrial conditions.

Another central research direction is metallurgical phase transformation and microstructure evolution in hybrid welds. Unlike pure laser welding, which often produces extremely high cooling rates and brittle martensitic zones in low-alloy steels, hybrid welding offers a broader thermal cycle. Studies from the 2000s showed that hybrid weld metal and heat-affected zones typically exhibit a mixture of bainitic and martensitic structures with improved toughness compared to pure laser welds (Harris & Norfolk, 2008; Jokinen, Vihervä, Riikonen, & Kujanpää, 2000; Katayama, Naito, Uchiumi, & Mizutani, 2007). The microstructural investigations were closely linked with mechanical performance studies. Tensile strength, impact toughness and fatigue life of hybrid welds in low-alloy steels became one of the most important applied research directions after 2005. German shipbuilding-related studies showed that fatigue strength of hybrid welds was comparable to or higher than that of conventional multi-pass arc welds, provided that weld toe geometry was properly controlled (Mahrle & Beyer, 2006; Petring, Fuhrmann, Wolf, & Poprawe, 2007; Wieschemann, Kelle, & Dilthey, 2003). In pipeline-oriented studies in the United States, attention focused on root pass integrity and resistance to hydrogen-assisted cracking in hybrid welded girth welds (Harris & Norfolk, 2008; Victor, Nagy, Ream, & Farson, 2009).

Since approximately 2010, a distinct new research direction has been the digitalization and real-time monitoring of hybrid welding processes. Fiber lasers with output powers of 15–30 kW, together with high-speed cameras, photodiodes and spectroscopic sensors, enabled real-time observation of keyhole behavior, arc stability and plume formation. Research groups in Germany and China introduced closed-loop control systems that automatically adjusted laser power and arc current in response to signal fluctuations (Gu, Li, H., & Li, L. J., 2013; Petring, 2013; Reisgen, Olschok, Jakobs, & Engels, 2016). By the early 2020s, this logic evolved into the concept of a "digital twin" of the hybrid weld pool, in which numerical models are continuously corrected by live sensor data.

A further applied research direction concerns hybrid welding in combination with additive and narrow-gap technologies. In the late 2010s, hybrid laser-arc heat sources began to be investigated for directed energy deposition of steel and for narrow-gap hybrid welding of thick low-alloy plates above 20–40 mm (Shelyagin et al., 2018; Üstündağ, Fritzsche, Avilov, Gumenyuk, & Rethmeier, 2018a; Zhang, Li, Gao, & Zeng, 2017). These studies aim at further reducing the number of passes and lowering total heat input in massive steel structures for energy and offshore applications.

Taken together, these scientific directions show that research on hybrid welding of low-alloy steels developed in a coherent manner: from physical heat-source interaction and thermal modeling in the 1990s, through metallurgy and defect control in the 2000s, to digital monitoring, control and integration with advanced manufacturing systems in the 2010s–2020s. This body of research formed the scientific foundation for the large-scale industrial applications that will be examined in the following section.

4. Industrial Development and Practical Applications of Hybrid Laser-Arc Welding of Low-Alloy Steels.

The transition of hybrid laser-arc welding from experimental technology to an industrial method for low-alloy steels unfolded unevenly and over a long period. Although the physical principle had been demonstrated in the late 1970s, nearly twenty years passed before hybrid welding entered stable production environments. This delay was not accidental. It reflected the slow maturation of high-power laser sources, the conservatism of heavy industries, and the high economic risks associated with introducing laser-based systems into serial steel fabrication.

In the early 1990s, the introduction of laser and hybrid welding in shipbuilding was primarily constrained by the strict regulatory framework imposed by classification societies, notably Lloyd's Register, whose construction rules were based on conventional welding technologies (Gerritsen & Howarth, 2005). A 1992 European feasibility study identified regulatory acceptance as the main barrier, since laser welding had been applied industrially only in very limited, non-structural ship components. To address this, a second collaborative project was launched with the direct involvement of classification societies, focusing on butt and fillet welds on panel lines and aiming to demonstrate reduced distortion and rework despite high equipment costs. By 1996, this effort resulted in the first formal approval guidelines for CO_2 laser welding in ship construction, later adopted by Lloyd's Register. Subsequent EU-funded projects further extended this framework to quality assurance and non-destructive testing, enabling cautious but structured regulatory acceptance of advanced welding processes.

The development of hybrid laser-arc welding in European shipbuilding was driven by a sequence of EU-funded research and development programmes initiated in the early 1990s and consolidated within the 6th and 7th EU Framework Programmes (FP6 and FP7), including projects such as L-SHIP, TRANSLAS, SANDWICH, DOCKLASER, InterSHIP, and BESST. A decisive breakthrough occurred in the late

1990s with the introduction of laser-arc hybrid welding, which overcame the gap-tolerance and robustness limitations of purely laser-based processes.

Meyer Werft (Germany) became a flagship industrial implementer, replacing its conventional panel line with a hybrid laser welding facility in 2000, resulting in substantial improvements in weld quality, process stability, and productivity (Acherjee, 2018a; Gerritsen & Howarth, 2005; Reisgen, Olschok, & Turner, 2014). These panels, often exceeding 20 m in length, required strict geometric tolerances for automated block assembly (Figure 4). Hybrid welding made it possible to maintain these tolerances without extensive post-weld thermal correction. By the end of the 2000s, hybrid laser-arc welding had become a routine production option for selected structural joints at Meyer Werft.

Figure 4. Laser arc hybrid welded steel panels and stiffeners used for fabrication of ships at Meyer-Werft GmbH (Acherjee, 2018b, p. 225).

Outside Germany, Denmark and Finland followed slightly later (Acherjee, 2018a; Kah, Salminen & Martikainen, 2011). At the Odense Steel Shipyard, hybrid laser-arc welding was tested and introduced between 2005 and 2008 for container ship and offshore vessel panels made of 8–10 mm structural steel. The hybrid welding offered a way to compensate for rising labor costs by shortening production cycles in panel fabrication. In Aker Yards (Finland), hybrid welding entered ship production in Turku after 2006. There it was applied to low-alloy steels in the 8–12 mm range, particularly for ice-class structures. Finnish studies stressed improved fatigue performance at welded stiffener joints, which was critical for ships operating under cyclic ice loads.

At nearly the same time, a different industrial logic shaped the introduction of hybrid laser-arc welding in the United States (Harris & Norfolk, 2008; Victor, Nagy, Ream, & Farson, 2009). There, the focus was not on plate panels but on pipeline girth welding. Between 2004 and 2006, the Edison Welding Institute carried out large-scale hybrid welding trials for transmission pipelines made of low-alloy steels of grades API X65-X70. These trials, supported by U.S. federal safety authorities, used fiber lasers of 8–10 kW combined with MAG arcs to weld pipes with wall thicknesses of 9–14 mm. The hybrid root pass replaced several conventional arc passes. Field data showed that total welding time per joint dropped by roughly one third while low-temperature impact toughness remained within qualification limits for gas transmission. Despite its technical success, hybrid welding did not become standard in U.S. pipeline construction because of conservative certification rules and the high investment cost of laser systems.

After 2010, hybrid laser-arc welding entered a new phase associated with thick low-alloy steels for energy and offshore applications. This shift became possible only after the widespread industrial availability of fiber and disk lasers in the 15–30 kW range. One of the most important new fields was the fabrication of wind-energy towers in Germany (Brunner-Schwer, Üstündağ, Bakir, Gumenyuk, & Rethmeier, 2023). At the research led by Michael Rethmeier and Andrey Gumenyuk began around 2012 and focused on hybrid laser-MAG welding of steels with thicknesses of 20–30 mm, typical for wind-tower shells. Between 2012 and 2020, these researchers demonstrated stable single- and double-sided hybrid welding of 25 mm plates using laser powers of 16–24 kW. Their work showed that groove volume could be drastically reduced and that the number of welding passes could be lowered from eight to ten with submerged arc welding to only two or three hybrid passes. At the same time, residual stress and fatigue behavior under cyclic loading were carefully investigated, as these factors determine the lifetime of wind-energy structures.

The largest scale of hybrid laser-arc welding of low-alloy steels developed in China after approximately 2013–2015. Unlike Europe, where hybrid welding remained concentrated in selected niches, China introduced it directly into heavy offshore and energy structures (Acherjee, 2018b; Liu et al., 2024; Ma, Cheng, Ning, Zhang, & Na, 2021). At fabrication yards in Nantong and Yantai, hybrid welding systems were installed for offshore wind monopiles, transition pieces, and large tower sections made of 30–40 mm low-alloy steels. These systems combined fiber lasers with optical powers of 25–32 kW and high-current MAG arcs. In these applications, more than ten submerged arc welding passes were replaced by two or three hybrid passes. This reduced production time for a single circumferential joint from several hours to well below one hour and significantly lowered energy consumption and distortion in massive steel shells.

By the early 2020s, hybrid laser-arc welding of low-alloy steels had become a stable industrial technology in several high-performance sectors: European ship panel production, selected pipeline projects in North America, wind-energy tower fabrication in Germany, and large offshore and energy structures in China. At the same time, it did not replace classical arc or submerged arc welding on a universal scale. Instead, it occupies a clearly defined technological niche where thick sections, cyclic loading, strict geometric tolerances, and productivity requirements make the economic advantages of hybrid welding decisive.

5. Hybrid Laser-Arc Welding and Sustainable Development.

The connection between hybrid laser-arc welding of low-alloy steels and sustainable development did not exist at the moment when the technology first emerged in 1970s–1980s. For the first two decades, hybrid welding developed almost entirely within a framework of productivity, penetration depth, and process stability. The sustainability dimension became explicit only much later, after the adoption of the United Nations Sustainable Development Goals (SDGs) in 2015, when industrial technologies began to be evaluated not only by economic efficiency but also by energy use, material efficiency, and environmental impact.

From a historical perspective, the sustainability relevance of hybrid laser-arc welding rests primarily on three factors: reduced heat input, reduced material consumption, and extended service life of welded steel structures. These factors appeared as practical engineering advantages long before they were framed in sustainability language, but after 2015 they began to be interpreted within the SDG framework.

The reduction of heat input is one of the oldest documented advantages of hybrid welding. Already in the early shipbuilding applications in Germany in the mid-2000s, hybrid welding allowed three- or four-pass MAG joints to be replaced by a single hybrid pass in low-alloy steels of 10–12 mm thickness. This directly meant lower electrical energy consumption per meter of weld and narrower heat-affected zones. In historical terms, this corresponds most closely to SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production), even though these categories were defined only later.

Material savings became especially visible after hybrid welding moved into thick-section energy structures in the 2010s. In wind-tower fabrication in Germany, as demonstrated by the research of Michael Rethmeier and Andrey Gumenyuk at the reduction of groove volume when welding 20–30 mm low-alloy steels led to a drastic decrease in deposited filler metal. In traditional submerged arc welding, the wide V-groove geometry required large volumes of wire and flux. Hybrid laser-arc welding allowed narrow grooves and two- or three-pass joints instead of eight to ten passes. In sustainability terms, this translates directly into lower consumption of consumables and lower embodied energy in the welded joint.

A similar effect appeared on a much larger scale in Chinese offshore wind and energy structures after 2015. At fabrication yards in Nantong and Yantai, hybrid welding of 30–40 mm low-alloy steels reduced the number of welding passes by a factor of four to five compared with submerged arc welding. This led not only to shorter production times but also to substantial reductions in total electrical energy used per circumferential joint. In sustainability language, this fits directly into SDG 9 (Industry, Innovation and Infrastructure) and SDG 13 (Climate Action), since lower energy consumption per unit of welded structure contributes to reduced indirect greenhouse gas emissions.

The third sustainability dimension is service life. Hybrid laser-arc welding produces narrower heat-affected zones and more controlled microstructures than many conventional multi-pass arc procedures. This has direct consequences for fatigue resistance. In shipbuilding and wind-energy applications, where low-alloy steels are exposed to long-term cyclic loading, fatigue life is one of the main determinants of structural longevity. German and Finnish shipbuilding studies from the late 2000s already showed that hybrid welds at stiffener joints exhibit comparable or higher fatigue strength than conventional arc welds. In wind-energy towers, the work conducted in Berlin after 2012 explicitly addressed fatigue performance under realistic cyclic loading conditions. From a sustainability perspective, extending the service life of large steel structures reduces the need for early replacement and lowers the long-term material footprint of infrastructure.

Historically, it is important to underline that hybrid laser-arc welding was not developed as a “green” technology in the modern sense. Its sustainability effects are mostly a secondary result of engineering optimization aimed at productivity and quality. Only after the global diffusion of the SDG framework did these technological advantages begin to be interpreted in environmental and resource-oriented terms. In this sense, hybrid welding represents a typical case of a technology whose sustainability significance became visible only retrospectively, through changing societal and policy frameworks.

Today, hybrid laser-arc welding of low-alloy steels can be seen as a mature industrial technology that aligns well with several core SDGs without having been explicitly created for that purpose. Its historical trajectory shows how industrial efficiency, once pursued mainly for economic reasons, can later acquire a broader environmental and social meaning.

6. Interaction Between Scientific Research and Industrial Implementation.

The historical development of hybrid laser-arc welding of low-alloy steels shows a clear and persistent gap between scientific research and industrial implementation. Although the physical principle of hybrid interaction was formulated in 1980, stable industrial deployment did not begin until nearly twenty years later. This delay reflects not only technical barriers but also institutional, economic, and regulatory constraints.

In the early phase, research on hybrid processes was concentrated almost entirely in university laboratories and national research institutes. Experimental work required expensive laser systems, which in the 1980s and early 1990s were available only at a limited number of sites. Even when laboratory experiments demonstrated deeper penetration and improved stability, industry remained cautious. For manufacturers of heavy steel structures, hybrid welding represented a high-risk investment with uncertain economic return. Conventional arc welding, by contrast, was already deeply integrated into production systems, standards, and worker qualification frameworks.

A more systematic interaction between research and industry began to form only in the late 1990s, when institutes such as the Fraunhofer Institute for Laser Technology and the Edison Welding Institute began to act as intermediaries between laboratory science and production. In Germany, Fraunhofer ILT developed hybrid laser-arc welding not only as a research topic but as an industrial service technology. This institutional model, in which research institutes operate hybrid systems directly on industrial sites, was a decisive factor in building trust in the new technology.

In the United States, the transfer mechanism followed a different logic. At Edison Welding Institute, hybrid welding was introduced through industry-funded projects aimed at solving concrete production problems, particularly in pipeline construction. The hybrid process was tested under field conditions, not only under laboratory constraints. However, even technically successful demonstrations did not guarantee rapid diffusion. Pipeline welding in the United States is governed by strict regulatory frameworks, and the adoption of a new welding process requires long and costly qualification campaigns. As a result, hybrid welding remained confined to selected projects rather than becoming a universal pipeline standard.

The wind-energy case in Germany illustrates a third pattern of science–industry interaction. Here, hybrid laser-arc welding entered industrial production not through incremental panel fabrication but through a new energy sector that was expanding rapidly after 2010. Research at under the leadership of Michael Rethmeier and Andrey Gumenyuk addressed problems that were directly relevant for wind-tower manufacturers: reduction of groove volume, control of residual stresses, and fatigue resistance in thick low-alloy shells. In this case, the growth of a new industrial sector created a window in which a new welding technology could be adopted without displacing deeply entrenched older production routines.

In China, the interaction between science and industry has followed yet another trajectory. Since the mid-2010s, hybrid laser-arc welding has been integrated into massive offshore and energy-structure fabrication almost simultaneously with its scientific development. Large state-supported enterprises, together with university laboratories such as the Harbin Institute of Technology, have treated hybrid welding as a strategic manufacturing technology. The scale of Chinese industrial deployment allowed rapid feedback between production problems and scientific optimization, shortening the traditional gap between research and implementation.

Across all these cases, one structural feature remains constant. Hybrid laser-arc welding did not move into industry simply because it was technically superior in isolated experiments. It required a specific institutional setting in which research organizations, equipment suppliers, and manufacturing companies could operate within shared development projects over several years. Where such structures were absent, hybrid welding diffused slowly or remained confined to niche applications.

From a historical perspective, the interaction between science and industry in the field of hybrid welding demonstrates that technological feasibility alone is not sufficient for industrial adoption. Long-term cooperation, regulatory acceptance, capital investment capacity, and the emergence of new industrial demand all played decisive roles in determining when and where hybrid laser-arc welding of low-alloy steels became a stable production technology.

7. Discussion.

The historical trajectory of hybrid laser-arc welding of low-alloy steels shows a pattern that differs from many classical welding technologies. It did not emerge as a direct response to a shortage of welding methods but as a result of cumulative limitations that became visible only after both laser welding and arc welding had independently reached high levels of maturity. By the late 1970s, laser welding offered penetration and speed but lacked tolerance to joint imperfections. Arc welding offered adaptability but was constrained by heat input and productivity in thick sections. Hybrid welding emerged precisely at the intersection of these unresolved limitations.

What is particularly notable is the long temporal gap between scientific formulation and industrial stabilization. The physical foundation of hybrid welding was clearly articulated by 1980 (Steen, 1980), yet stable industrial deployment began only around the early 2000s (He et al., 2025; Petring, 2013).). This delay cannot be explained by technological immaturity alone. It reflects the high capital cost of laser systems, the conservative nature of steel-intensive industries, and the rigid structure of welding standards and certification systems. Hybrid welding had to prove not only its technical capability but also its reliability under long production cycles, variable joint conditions, and strict quality regulations.

Another important feature of its historical development is the dependence on sector-specific demand. Hybrid welding did not spread uniformly across manufacturing. It became established first in ship panel production, where distortion control and dimensional accuracy are decisive (Jokinen, Vihervä, Riikonen, & Kujanpää, 2000; Olschok, Reisgen, & Dilthey, 2007; Wieschemann, Kelle, & Dilthey, 2003). It then entered pipeline welding under regulatory pressure for productivity gains (Gook, Gumenyuk, & Rethmeier, 2014; Harris & Norfolk, 2008; Zhenglong, Caiwang, Yanbin, & Zhongshao, 2013), and later moved into wind-energy (Brunner-Schwer, Üstündağ, Bakir, Gumenyuk, & Rethmeier, 2023) and offshore structures when thick-wall shells and high cyclic loading created new performance requirements that conventional submerged arc welding could not satisfy economically (Bunaziv, Akselsen, Frostevarg, & Kaplan, 2019; Bunaziv, Ren, & Olden, 2023; Liu et al., 2024).

In this sense, hybrid laser-arc welding developed not as a universal replacement for arc welding but as a targeted solution for structurally demanding applications of low-alloy steels.

The national patterns also reveal different models of technological diffusion. In Germany and Northern Europe, hybrid welding grew through close cooperation between research institutes and shipyards or wind-tower manufacturers (Bunaziv, Akselsen, Frostevarg, & Kaplan, 2019; Gook, Gumenyuk, & Rethmeier, 2014; Petring, 2013). In the United States, it was tested through regulatory-driven pipeline projects but remained limited by certification barriers. In China, it was integrated rapidly into large-scale offshore and energy fabrication, supported by state-backed industry and research institutions. These different pathways show that hybrid welding is shaped as much by industrial organization and policy as by technical parameters.

From a longer historical perspective, hybrid laser-arc welding can be seen as a transitional technology. It stands at the boundary between classical fusion welding and digitally controlled, sensor-driven manufacturing systems. Its development in the 2010s and 2020s, with the integration of real-time monitoring and adaptive control, suggests that hybrid welding is no longer just a combination of two heat sources but part of a broader transformation of steel fabrication toward data-driven production.

Conclusions.

The historical development of hybrid laser-arc welding of low-alloy steels began with the scientific formulation of arc-augmented laser processing in the late 1970s and unfolded over more than four decades. During the first two decades, hybrid welding remained primarily a research topic, shaped by advances in laser physics, arc plasma modeling, and numerical simulation. Only with the maturation of high-power industrial lasers, digital control systems, and sensor technologies did it become a viable industrial welding method.

Its industrial stabilization occurred unevenly across sectors and countries. In European shipbuilding, hybrid welding became a practical solution for reducing distortion and increasing panel-line productivity. In North American pipelines, it demonstrated technical feasibility but remained constrained by regulatory and economic factors. In German wind-energy manufacturing, it provided a response to the challenge of welding thick low-alloy shells under cyclic loading. In China, it reached the largest scale of industrial deployment in offshore wind and energy structures, supported by large fabrication yards.

Hybrid laser-arc welding did not replace conventional arc or submerged arc welding as universal methods. Instead, it established itself as a high-performance technology for demanding applications where thick sections, fatigue resistance, geometric precision, and productivity requirements converge. Its historical trajectory shows that the success of a welding technology depends not only on physical principles and equipment performance but also on institutional networks, industrial structure, and sector-specific demand.

From the perspective of sustainable development, the significance of hybrid welding became visible only retrospectively. By reducing heat input, consumable use, and distortion, and by extending the service life of large steel structures, it aligns with contemporary sustainability goals even though it was not created with environmental objectives in mind.

In historical terms, hybrid laser-arc welding of low-alloy steels represents a mature example of how late twentieth-century laser science, classical welding engineering, and twenty-first-century digital manufacturing converged into a stable industrial technology shaped equally by science, industry, and long-term structural change.

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Гібридне лазерно-дугове зварювання низьколегованих сталей: Від наукової концепції до промислової технології (1970-ті – 2020-ті роки)

Анотація. *У статті досліджено історичний розвиток гібридного лазерно-дугового зварювання низьколегованих сталей від формулювання гібридної концепції наприкінці 1970-х років до її становлення як промислової технології на початку XXI ст. Виділено дві взаємопов'язані, але історично не синхронні траєкторії: еволюцію фундаментальних і прикладних наукових досліджень лазерно-дугової взаємодії та подальше формування сталих промислових застосувань у суднобудуванні, трубопровідному зварюванні, виготовленні* *вітроенергетичних веж, а також енергетичних конструкцій. На основі наукових публікацій, інституційних звітів і задокументованих промислових впроваджень у Німеччині, Данії, Фінляндії, США та Китаї реконструйовано шлях переходу гібридного зварювання від лабораторних експериментів до серійного виробництва у секторах зі складними конструктивними вимогами. Особливу увагу приділено ролі провідних наукових центрів, а також процесам трансферу технологій. Показано, що істотна часова затримка між науковим обґрунтуванням і промисловим впровадженням зумовлювалася не лише рівнем розвитку лазерного обладнання, а й інституційним консерватизмом, бар'єрами сертифікації та високою капіталомісткістю лазерно-орієнтованих виробничих систем. Окремо проаналізовано секторальний характер поширення технології, що пояснює, чому гібридне лазерно-дугове зварювання спочатку закріпилося у європейському суднобудуванні, згодом – у вибраних трубопровідних проєктах Північної Америки, далі – у виробництві вітроенергетичних веж у Німеччині, а найбільшою мірою – в офшорних та енергетичних конструкціях у Китаї. Також розглянуто принципово важливе переосмислення цієї технології в контексті Цілей сталого розвитку Організація Об'єднаних Націй, із акцентом на зниження тепловкладення, скорочення витрат зварювальних матеріалів, зменшення деформацій та подовження ресурсу експлуатації великих сталевих конструкцій. Доведено, що гібридне лазерно-дугове зварювання не сформувалося як універсальна альтернатива традиційним дуговим або підфлюсовим процесам, а як високопродуктивне цільове рішення, детерміноване взаємодією наукових знань, промислового попиту, інституційних мереж і довготривалих структурних змін у сталемістких галузях виробництва.*

Ключові слова: *гібридне лазерно-дугове зварювання; низьколеговані сталі; історія зварювальних технологій; лазерна обробка матеріалів; взаємодія науки та промисловості; сталий розвиток*

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