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Analysis of modern methods for reducing welding residual stresses

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Abstract

This paper presents a systematic comparative analysis of the physical mechanisms governing internal stress generation in structural weldments, evaluates the efficiency of existing stress relaxation techniques, and provides scientific substantiation for promising dynamic approaches aimed at extending the operational life of welded structures. The research methodology is based on the synthesis of thermomechanical models of the welding thermo-deformation cycle, dislocation concepts of micro-plastic metal flow, and an analytical comparison of thermal, mechanical deformation, and vibratory technologies according to stress relief depth, energy demand, and structural degradation risks. It was established that conventional post-weld tempering of creep-resistant alloy steels under prolonged holding leads to the dissolution of strengthening nano-carbides and their boundary coagulation, resulting in a 4 – 5-fold reduction in long-term creep resistance. Surface plastic deformation methods, such as weld rolling and ultrasonic impact treatment, induce beneficial compressive stresses but remain restricted to a shallow depth of 1.5–2.0 mm or require extreme contact loads, whereas standard electromechanical vibration treatment with monochromatic excitation proves ineffective for thick-walled, high-rigidity structures with natural frequencies exceeding 200 Hz. Consequently, the transition toward dynamic pulse excitation is substantiated, as it generates shock deformation waves with steep-fronted rise times, excites higher-order spatial poly-harmonics, refines primary solidification dendrites by 25–32%, and relieves peak macro-stresses by 60 – 80%. The scientific novelty lies in determining the physical regularities of multi-mode dynamic stress relaxation within welded concentration zones through non-linear wave processes and intensified dislocation mobility without prolonged resonant structural overloading. The practical significance of the obtained results enables the justified selection of resource-saving stress relief technologies for heavy-duty and thick-walled fabrications, eliminating expensive furnace annealing while minimizing dimensional distortion.
Keywords: welding residual stresses, thermo-deformation cycle, vibratory stabilization, dislocation mobility, shock-wave effect.

Introduction

The presence of high tensile residual macrostresses (Type I), whose magnitude in welded joints frequently approaches or exceeds the standard yield strength of the parent metal [1, 3, 5, 18, 21], significantly impairs structural performance. In combination with operational cyclic loads and geometric seam stress concentrators, they act as the driving force for the initiation and accelerated growth of fatigue cracks [7, 9, 21], induce loss of dimensional precision and distortion during machining or initial service loading [1, 10, 22], and trigger stress-corrosion cracking in aggressive working environments [16, 21]. This problem is particularly critical in thick-walled welded structures and tubular components [10, 15], where inherent welding stresses are superimposed onto technological stresses from prior forming, creating a complex bi-axial or tri-axial stress state and an elevated risk of premature failure [1, 18, 19].

Analysis of recent research and publications

Ensuring the operational reliability, cyclic fatigue life, and geometric stability of welded metal structures necessitates the mandatory implementation of technological measures aimed at reducing or redistributing residual welding stresses [1, 10, 11, 21, 22]. Depending on the execution stage and the underlying physical mechanisms, all methods for mitigating the internal stress-strain state (SSS) are classified into thermal, mechanical (deformation), vibrational, and combined multi-physical technologies [11, 22, 27]. The most conventional and standardized method for residual stress relief remains post-weld heat treatment (PWHT), primarily global or localized high tempering and annealing [11, 13, 18, 21, 22]. In this process, the structural assembly is heated to temperatures of 600 – 700 °C (governed by the steel alloy composition, such as 670 – 690 °C for 12% Cr creep-resistant steel), soaked for a specified design duration (1–3 hours or longer), and subsequently cooled at a controlled slow rate [11, 13]. As the temperature increases, the yield strength of the material (σ_T) decreases drastically, and the peak residual stresses, upon exceeding this thermally reduced threshold, relax via localized macro- and micro-plastic deformation mechanisms [1, 18]. Experimental and theoretical studies demonstrate that over 70 – 80% of stress relaxation occurs during the heating stage and within the initial 1 – 2 hours of isothermal soaking; further extension of holding time yields virtually no additional reduction in the final level of macroscopic residual stresses [21].

When applying thermal methods, an engineering compromise between material toughness and creep rupture strength must be attained, as thermal activation stabilizes the microstructure via the precipitation of *MX(V, Nb)(C, N*), carbonitrides that pin mobile dislocations through the Orowan strengthening mechanism [17, 24]. However, excessive thermal holding periods (exceeding 32 hours) trigger carbide coarsening via Ostwald ripening, characterized by the agglomeration of $M_{23}C_6$ boundary particles up to 100 – 500 nm and the simultaneous dissolution of fine intragranular strengthening nanocarbides (see Fig. 1) [24]. This degradation induces significant matrix softening and deteriorates long-term creep rupture strength despite maintaining impact toughness [24]. Within an optimal soaking range of 8–16 hours, finely dispersed MX precipitates establish formidable barriers against dislocation creep; conversely, extending heat treatment past 32 hours results in the near-total depletion of fine intragranular precipitates and the breakdown of subgrain dislocation networks [24]. Consequently, Orowan threshold stresses decrease, precipitating a 4 – 5-fold reduction in time-to-rupture under elevated-temperature service conditions [24].

Multi-pass weldments also exhibit thermal stability inversions: in the as-welded condition, interpass HAZ regions remain softer due to secondary austenitization [17, 24], whereas prolonged thermal exposure (exceeding 12 hours) reverses this relationship, rendering the HAZ more creep-resistant than the weld center owing to its refined prior austenite grain size and stabilized carbide distribution [24]. Significant industrial drawbacks of thermal treatment include: severe energy consumption and protracted production schedules reaching 8 – 12 hours [11, 13, 18, 21, 22]; surface oxidation scale demanding abrasive grit-blasting that reintroduces harmful superficial tensile stresses [11]; thermal distortion and geometric buckling of asymmetric or thin-walled assemblies caused by unconstrained thermal expansion [3, 11]; furnace dimensional constraints preventing the processing of large vessels, pipelines, and skeletal frames [2, 4, 8]; and detrimental carbon diffusion causing decarburization layers across dissimilar steel weld interfaces [11].

Mechanical post-weld mitigation techniques rely on the artificial generation of tensile plastic strains across the weld metal and the heat-affected zone to counteract the longitudinal shrinkage force F_{yc} [13, 22, 25]:

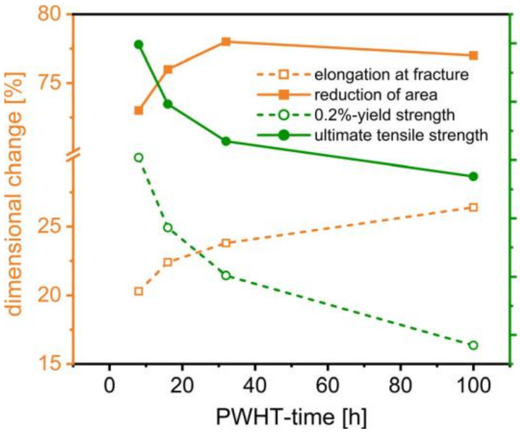
– static loading (stretching, bending): Executed by applying global external tensile forces to the welded assembly before or immediately after joint completion [1, 13, 22], which reduces residual peak tensile stresses in the active zone while generating favorable compressive fields near geometric notches [1, 10]; however, this approach requires massive, high-tonnage pressing fixtures, fundamentally limiting its applicability for complex 3D structures [22];

– weld rolling: Involves localized plastic compressive deformation of the weld crown or adjacent HAZ utilizing cylindrical or contoured rollers [9, 11]. Introducing through-thickness compressive deformations of fractions of a percent flattens the longitudinal residual stress profile, neutralizing peak tensile zones or shifting them into compression [9, 11]. Key limitations include the requirement for excessive contact loads up to 150 – 200 kN for plate thicknesses exceeding 10 – 12 mm, risks of localized over-rolling accompanied by reverse distortion, an associated 15 – 20% reduction in bend ductility, and physical tool-access constraints along curved weld paths [10, 12, 13, 24]. Direct weld-crest rolling with a profiled roller induces compressive stresses within the weld core and eliminates plate angular distortion at lower loads of 25 – 50 kN, whereas side-rolling the HAZ with flat dual rollers exhibits inferior efficiency due to high transverse alignment sensitivity (see Fig. 2) [25];

– peening and high-velocity impact deformation: Interpass or post-weld percussive hammering of the cooling weld deposit using pneumatic strikers at impact velocities of 6 – 7 m/s to 25 – 30 m/s induces planar flattening strains that convert residual tension into compression [2, 3]; nonetheless, it provokes superficial strain-hardening, exhausts local dislocation plasticity, and demands rigorous calibration of the specific impact energy (a/δ) to prevent cold embrittlement and a 15 – 20% drop in bend angles [26];

– explosive and magnetic pulse treatment: utilizing contact strip explosive charges or pulsed electromagnetic drivers propagates an elastoplastic shock wave through the joint, attenuating peak stresses and elevating cyclic endurance [2, 4]. Wider industrial adoption is hampered by strict explosion safety regulations, detonation chamber requirements, and inferior technological flexibility [2, 4];

– ultrasonic impact treatment: transmitting high-frequency acoustic oscillations coupled with mechanical needle impact (frequencies above 20 kHz) eliminates up to 80 – 100% of residual tensile stresses in the superficial layer (depths up to 1.5 – 2.0 mm) while enhancing fatigue durability [11, 21, 22]; its main drawbacks are the shallow treatment depth, restricted acoustic source power, and prohibitive labor intensity for heavy, multi-pass structures [2, 4, 22].



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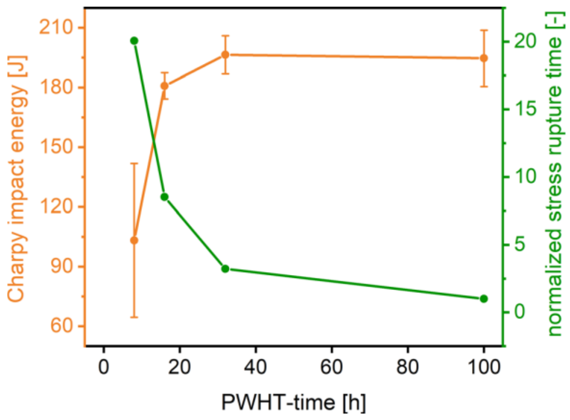

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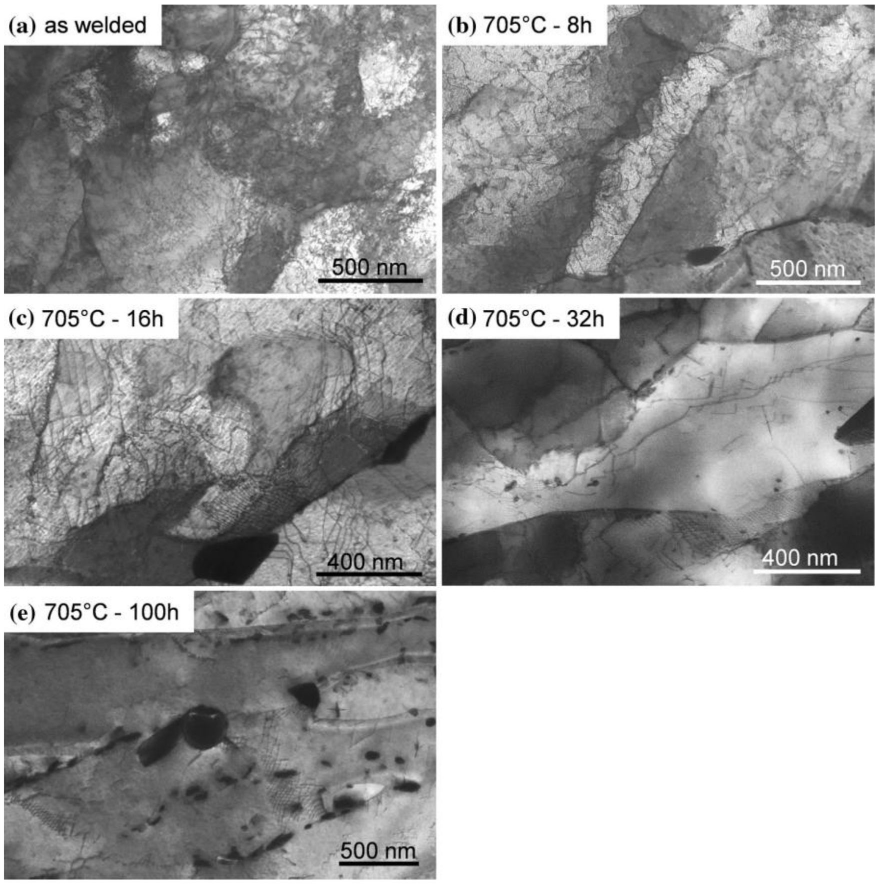
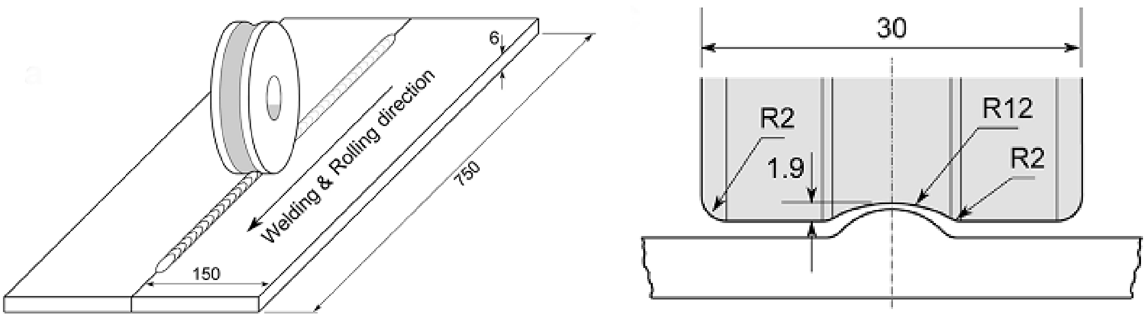


c)

Fig. 1. The effect of the duration of post-weld heat treatment (at 705 °C) on the microstructure and complex of mechanical properties of the weld metal of 2.25Cr-1Mo-0.25V steel: a) change in strength and plastic characteristics depending on the holding time; b) comparative dynamics of impact toughness and long-term creep; c) STEM micrographs of the evolution of the dislocation structure and size of MX carbidonitriles



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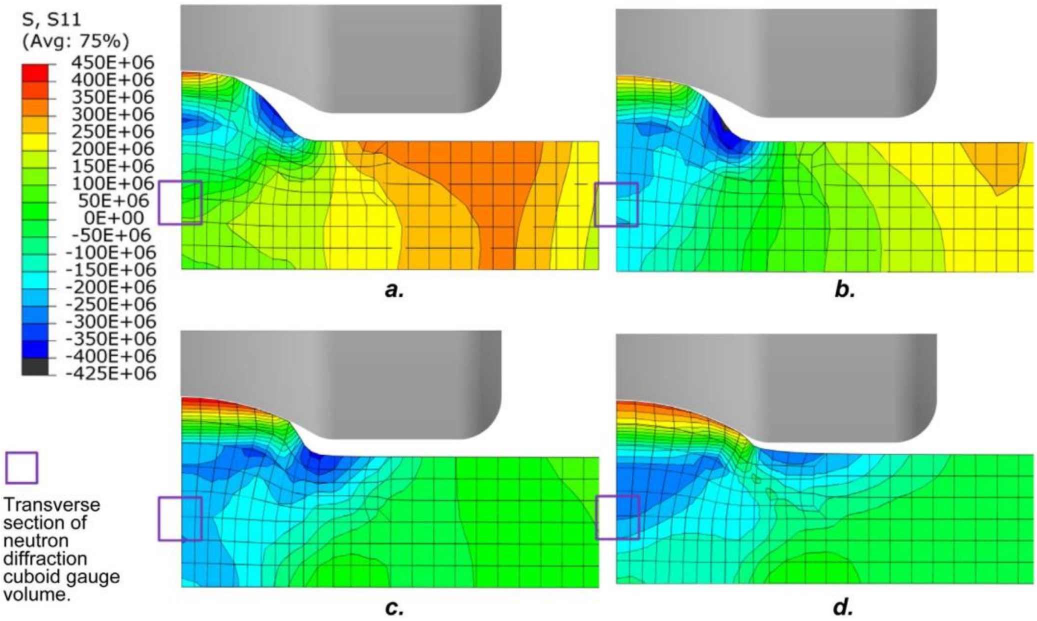

b)

Fig. 2. Rolling of a welded seam with a profile roller [25]: *a*) – three-dimensional diagram of the position of the roller on the seam and geometric parameters of the profile roller; b) – 2D maps of the distribution of longitudinal stresses σ_x in the seam zone at different loads (25, 50, 100, 150 kN)

Vibratory Stress Relief (VSR) serves as an economically viable, energy-efficient alternative to conventional furnace annealing [10, 11, 20, 22] and branches into two fundamental operational strategies:

1. Post-weld vibratory stress relief: the finished component is mounted on elastomeric isolators, and an eccentric unbalance exciter drives it at structural resonant frequencies [11]. Cyclic dynamic stresses σvib superimpose onto existing internal residual stresses σres [11, 14]. In peak tension zones, the microyielding threshold is surpassed:

$$\sigma_{res} + \sigma_{vib} \geq \sigma_T^{cyc}, \tag{1}$$

which triggers dislocation glide, microplastic relaxation, and elastic strain energy dissipation [11, 22]. Macroscopic residual stresses of Type I decrease by 50–60%, and intergranular stresses of Type II decrease by 40 –45%, establishing dimensional stabilization while cutting energy consumption by a factor of 40 – 50 and process time by a factor of 15 – 20 relative to furnace heating [11, 22];

2. Vibration during welding: introducing low-frequency dynamic oscillations (f = 50...150 Hz, A = 0.5–2.0 mm) directly during arc execution and pool solidification mechanically breaks developing columnar dendrites, refining the microstructure by 25 – 32%, accelerating hydrogen degassing, reducing pore formation, and mitigating cold and hot cracking susceptibility [11, 16, 18]. As-welded residual stresses are lowered by 16 – 25% (and up to 2 – 2.5 times in localized zones), eliminating the requirement for energy-intensive preheating in hardenable structural steels [11, 16].

Advanced combined multi-physical technologies also encompass: thermo-vibrational treatment (combining mild heating to 140 – 210 °C with resonant vibrations, lowering peak stresses by 46 – 50% within 1–2 hours) [22, 23]; magneto-vibrational processing (superimposing a 0.5 – 2.0 T magnetic field to induce the magnetoplastic effect, achieving a 40 – 60% stress drop) [22]; and pulsed electro-treatment (short current impulses of 103...104 A/mm2 exerting an "electron wind" force that relaxes microscopic lattice strains within fractions of a second) [22].

Accurate monitoring and characterization of residual welding stress distributions rely on measuring elastic or released strains, followed by stress recalculation using Hooke's constitutive law [6, 26]. These evaluation techniques are structured into destructive, semi-destructive, and non-destructive categories [6, 22, 26]:

– Hole-drilling method (ASTM E837): employs a 3- or 6-element strain gauge rosette coupled with high-speed precision drilling of a hole (Ø1.5–2.0 mm, depth 1.0 – 2.0 mm) [6, 26]. This technique is accurate for stresses within 50–60% of σ_T; higher magnitudes induce localized plastic yield around the hole boundary, distorting measurement linearity [6, 26];

– Deep hole drilling (DHD): designed for heavy cross-sections up to 100 mm, involving the precision drilling of a reference hole through the component thickness, followed by coaxial core trepanning and diameter change mapping to resolve full-depth stress profiles [26];

– Contour method (CM): involves sectioning the welded part via wire electrical discharge machining (WEDM) along the plane of interest, scanning surface de-planing contours on a coordinate measuring machine, and feeding these displacement deviations as boundary conditions into a finite element model to construct full 2D cross-sectional normal stress maps [26];

Diffraction non-destructive methods: utilize atomic lattice plane spacings (d_{hkl}) as internal strain sensors governed by Bragg's law [18, 22, 26]:

$$n\lambda = 2d_{hkl}\sin\theta \ , \tag{2}$$

where represents λ the radiation wavelength, and θ is the Bragg diffraction angle [26].

X-ray diffraction (XRD) guarantees precision when resolving biaxial stress components ($\sin^2\varphi$) in superficial layers restricted to 10 – 30 µm [15, 26]. Neutron diffraction (ND), capitalizing on the neutral charge of thermal neutrons and their superior nuclear penetration, evaluates the full triaxial stress tensor (σ_x, σ_y, σ_z) non-destructively at depths reaching 50 mm in structural steels and 100 mm in aluminum alloys [13, 24, 26].

Aims of the article

Systematic comparative analysis of the physical mechanisms governing internal stress generation in structural weldments, evaluation of existing relaxation techniques, and scientific justification of advanced dynamic approaches based on non-linear hydraulic pulse excitation to enhance the operational durability of welded assemblies.

Methods

The study synthesizes thermomechanical and dislocation models of the welding thermo-deformation cycle, micro-plastic metal flow mechanics, multi-criteria analytical benchmarking of thermal, mechanical, and vibratory stress relief methods based on relaxation depth, energy consumption, and structural degradation risks, as well as the principles of fluid transient wave dynamics and non-linear pressure pulse generation.

Results

Among existing approaches for the dynamic regulation of weldment stress-strain states, introducing mechanical oscillations directly during arc burning and weld pool solidification represents the most technologically expedient method [10, 11, 28]. Low-frequency vibrations excite shear waves in the liquid melt and mushy zone [11, 28], inducing intense hydrodynamic mixing, dendrite fragmentation, and heterogeneous nucleation [11, 28]. This transforms coarse columnar grains into a refined equiaxed microstructure (decreasing average grain area by 25 – 32%), promotes hydrogen desorption, and reduces residual stresses by 16 – 25% relative to rigidly clamped welding [11, 16, 28]. Operational parameters center on a frequency bandwidth of 50 – 150 Hz (corresponding to the secondary structural resonance mode with peak shear at the joint) [26] and vibration amplitudes of 0.5 – 1.0 mm [11, 28]. Exceeding an amplitude of 1.2 – 1.5 mm is unacceptable due to molten pool spatter, shielding gas disruption, and solidification cracking [11, 16].

In industrial practice, vibration treatment is conventionally performed using electromechanical unbalance exciters [11, 20, 22], which possess severe physical drawbacks:

– Monochromatic harmonic waveform: sinusoidal oscillations transfer energy exclusively at a single resonant mode, requiring prolonged run times (15 – 45 min) and risking localized cyclic fatigue damage at vibration nodes [11, 22];

– Stiffness limitations: for heavy, thick-walled, or box-type weldments, fundamental natural frequencies exceed 200 – 400 Hz, where mechanical unbalance motors cannot generate the requisite dynamic excitation forces [20, 22];

– Operational reliability issues: unbalance shaft bearing assemblies experience premature mechanical failure under sustained, severe centrifugal loading [11, 12].

For massive 3D welded components, sinusoidal forces prove insufficient to overcome the Peierls-Nabarro barrier and unlock pinned dislocation tangles without inducing fatigue [11, 22]. They generate monochromatic sinusoidal oscillations, transmitting energy exclusively at a single resonant mode; this requires long operating durations (15 – 45 min) and risks inducing localized fatigue degradation at vibration nodes [11, 22]. Furthermore, in massive, tubular, or high-rigidity box-shaped weldments, fundamental natural frequencies exceed 200 – 400 Hz, where mechanical unbalance motors cannot produce the required dynamic force amplitudes due to bearing load failures caused by excessive centrifugal forces [20, 22]. Consequently, despite considerable research efforts, the issues of effective force action on rigid, large-scale structures utilizing poly-frequency non-linear impulses remain insufficiently explored, substantiating the necessity for developing novel dynamic methods and drives.

A promising scientific direction is the implementation of hydraulic pulse drives [27–33], which convert high-pressure fluid flow into periodic, steep-fronted shock pressure pulses, fundamentally transforming dynamic process capabilities [27 – 33]:

1. Generation of steep vibro-impact fronts: unlike smooth sinusoidal inputs, pressure pulses exhibit near-instantaneous rise times ($\Delta t \to 0$) transmitting high-amplitude shock deformation waves directly into the workpiece [27–33];

2. Poly-frequency excitation spectrum: the non-linear impulse profile simultaneously excites higher spatial harmonics, relieving low-frequency structural bending modes as well as high-frequency plate and stiffener vibrations [27 – 33];

3. Energy localization at stress peaks: high impact acceleration gradients cause localized stresses to exceed the dynamic yield point specifically within stress concentrations (HAZ, fusion boundaries), initiating dislocation mobility and annihilation without global fatigue overloading [27 – 33];

4. Superior force density: hydraulic pulse systems generate dynamic working forces spanning tens to hundreds of kilonewtons while maintaining compact modular exciter dimensions [27 – 33].

Conclusions

Based on the analysis of the current state of the art regarding the nature of residual welding stress formation, measurement methods, and stress-strain state (SSS) mitigation technologies, the following conclusions can be drawn:

1. Residual welding macrostresses (Type I) reach the yield strength of the parent metal and serve as the primary factor reducing cyclic fatigue life, promoting stress-corrosion cracking, and inducing geometric distortion in welded assemblies [1, 3, 7, 21].

2. Conventional post-weld heat treatment (PWHT) provides deep stress relaxation, but it is characterized by high energy consumption, prolonged cycle durations, surface scaling, thermal warping, and limited applicability to large-scale or field-assembled structures [11, 21, 22, 28]. Furthermore, prolonged holding times during PWHT in creep-resistant alloy steels induce the coarsening of strengthening nano-carbides and $M_{23}C_6$ precipitates, resulting in a severe degradation of long-term creep rupture strength [24].

3. In-process mechanical and vibration treatment methods applied directly during welding enable the refinement of the primary as-cast dendritic structure, lower final residual stresses, and partially eliminate energy-intensive preheating [11, 16, 28]. However, conventional electromechanical unbalance exciters generate purely harmonic oscillations, possess restricted force capacity, and prove ineffective for high-rigidity, thick-walled structures featuring high natural frequencies [11, 20, 22].

4. A promising scientific and engineering direction is the transition toward hydraulic pulse drives capable of generating high-power, non-linear vibro-impact pressure waves with steep-fronted rise times. This ensures the excitation of a broad poly-frequency oscillation spectrum, local dislocation un-pinning within stress concentration zones, and effective peak stress relaxation with minimal energy expenditure [22, 27–33].

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Бакалець Д.В., Поліщук В.В. Аналіз сучасних методів зниження залишкових зварювальних напружень.

У роботі проведено системний порівняльний аналіз фізичних закономірностей зародження внутрішніх напружень у металоконструкціях, оцінено ефективність існуючих способів їх релаксації та науково обґрунтовано перспективні динамічні підходи для підвищення експлуатаційного ресурсу зварних виробів. Методологія дослідження ґрунтується на узагальненні термомеханічних моделей зварювального термодеформаційного циклу, дислокаційних концепціях пластичної течії металів, а також на аналітичному зіставленні термічних, деформаційних та вібраційних технологій за критеріями глибини зняття напружень, енерговитрат і ризику структурної деградації матеріалу. Встановлено, що традиційний післязварювальний відпуск теплостійких легованих сталей за тривалої витримки спричиняє розчинення нанорозмірних зміцнюючих карбідів та їх коагуляцію на межах зерен, знижуючи опір тривалій повзучості у 4 – 5 разів. Механічні методи поверхневого пластичного деформування (прокатка, ультразвуковий наклеп), попри ефективне створення стискальних напружень, обмежені глибиною дії 1,5 – 2,0 мм або вимагають надмірних контактних зусиль, тоді як стандартна електромеханічна віброобробка монохроматичної дії виявляється малоефективною для товстостінних і жорстких оболонок із частотами понад 200 Гц. З огляду на це обґрунтовано доцільність переходу до динамічного імпульсного збудження, яке формує ударні хвилі деформації з крутим фронтом наростання навантаження, збуджує спектр просторових полігармонік, подрібнює первинні дендрити кристалізації на 25 – 32% і забезпечує релаксацію пікових макронапружень на 60 – 80%. Наукова новизна полягає у встановленні фізичних закономірностей багатомодового динамічного розвантаження зон концентрації зварювальних напружень шляхом активації нелінійних хвильових процесів та інтенсифікації дислокаційного руху без тривалого резонансного перевантаження металу. Отримані результати комплексного аналізу мають практичну значимість, оскільки дозволяють обґрунтовано обирати ресурсозберігаючі технології зняття напружень для великогабаритних та товстостінних конструкцій, виключаючи дорогий пічний відпал і мінімізуючи залишкове короблення.

Ключові слова: залишкові зварювальні напруження, термодеформаційний цикл, вібраційна стабілізація, рухливість дислокацій, ударно-хвильова дія.