



Research paper

A multimethod experimental investigation on HDPE materials and butt-welded joints for marine structural applications

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ABSTRACT

High-Density Polyethylene (HDPE) is increasingly considered for marine structural applications due to its corrosion resistance, weldability, and recyclability; however, its mechanical performance—particularly in recycled form and in welded joints—remains insufficiently characterized within the framework of ship classification society requirements. This study addresses these gaps through a comprehensive experimental investigation of virgin, recycled, and welded HDPE specimens. Two butt-welding techniques—machine-based fusion and manual extrusion welding—were applied to virgin HDPE panels and examined using consistent specimen geometries to enable a direct comparison between industrial and field-applicable processes. The mechanical behaviour of all specimen types was assessed through tensile testing, supported by Digital Image Correlation for full-field strain analysis and Infrared Thermography for detecting early damage and monitoring thermal energy release. Additional optical microscopy and Fourier-transform infrared spectroscopy provided insights into fracture morphology and chemical structure. The results demonstrate that recycled HDPE exhibits yield stress and stiffness comparable to those of virgin material within the linear-elastic range. Both welding technologies maintain the essential load-bearing capacity of the polymer, with extrusion welding showing enhanced joint stiffness—reflected in the increased Young's modulus of the welded region. By integrating mechanical, thermal, and chemical characterization with a critical examination of ship classification society requirements, this study expands the current framework for evaluating HDPE assemblies and offers new evidence supporting the use of recycled HDPE and alternative welding techniques in sustainable marine structural applications.

1. Introduction

Polyethylene (PE) is among the earliest synthetic polymers developed and remains one of the most widely employed materials across numerous industrial sectors and in everyday applications. Its widespread use is attributable to its favourable balance of mechanical properties, chemical resistance, processability, and relatively low production cost (Chen and Lin, 2021). Polyethylene is commonly produced in several grades distinguished by density—low-density (LDPE), medium-density (MDPE), and high-density (HDPE)—each exhibiting distinct mechanical behaviour and processability profiles. Among these, HDPE combines high strength-to-density ratio, impact resistance, and chemical stability, making it suitable for applications requiring

durability in harsh environmental conditions, such as marine environments (Fu et al., 2024, Lourmpas et al., 2024, Sanjuan et al., 2023). HDPE is commonly used as the outer sheath, which is the outermost layer of flexible pipes used in the offshore industry. These pipes (including risers, jumpers, and flowlines) are multilayer structures designed to withstand pressure, tension, continuous movement, corrosion, and harsh marine environments. Relevant studies have also examined the mechanical behaviour of HDPE components used in flexible pipe structures; within this structural context, Rabelo et al. (2015) investigated the axisymmetric instability of HDPE pipes under combined compressive loading and internal pressure. In the context of modern sustainable shipbuilding, besides the satisfaction of the mechanical and functional requirements of the intended application, the

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selection of construction materials is increasingly driven by the adherence to principles of environmental responsibility. Key considerations include recyclability at the end of the vessel's service life, low energy demand during processing, and minimal exploitation of natural resources during production (Nykiel et al., 2025). Fibre-reinforced polymers (FRPs), which are the most used materials for the construction of small-size vessels, represent a serious problem for the disposal of the small-size vessels at their end-of-life for the presence of thermoset matrix, which cannot be recycled (Krauklis et al., 2021). Thus, in order to follow the increasingly important trend of minimising environmental impact and promoting sustainable development in the boatbuilding industry, the introduction of eco-friendly materials, such as wood (Nasso et al., 2019, Corigliano et al., 2017, Corigliano et al., 2021), that is natural and recyclable material, is necessary. Within this context, the possibility of manufacturing HDPE from recycled feedstock contributes to a circular production model, reducing environmental burden and aligning with the objectives of the Green Shipbuilding approach. Despite these advantages, HDPE has only recently gained significant attention for relevant applications in the maritime sector, with a specific focus on workboat constructions (Fig. 1). Its appeal stems from its recyclability and low environmental impact and aligns with the broader effort to develop sustainable alternatives to traditional FRPs, which, although well established, pose challenges in terms of recyclability and end-of-life management (Firmanda et al., 2022).

Knowledge of the mechanical behaviour of HDPE is of paramount importance for its application in boats and small vessels, as it directly underpins structural design and classification requirements. In this context, among the ship classification societies that have developed dedicated rules for vessels with plastic hulls (Kafali, 2023), the present study focuses on the requirements issued by Registro Italiano Navale (RINA), Bureau Veritas (BV), and the Indian Register of Shipping (IRS) that explicitly address the use of HDPE (Registro Italiano Navale, 2023, RINA, 2023, Bureau Veritas, 2022, Indian Register of Shipping, 2024). Indeed, these societies have recently introduced tailored rules defining the mechanical properties, performance, and welding requirements necessary for the classification of HDPE hulls.

Beyond the use of virgin material, HDPE can also be produced from recycled sources by reprocessing scraps derived from previous applications (Lei et al., 2007, Sánchez-Soto et al., 2008). Although recycled HDPE (r-HDPE) is not formally recognised for structural use in boatbuilding by most certification bodies (e.g., by RINA and IRS), several studies have explored its potential applicability particularly for non-critical components (Saputra et al., 2021, Ridwan et al., 2022). Additionally, Tesfaw et al. (2022) investigated the incorporation of rHDPE in pipe-fitting compounds and reported acceptable short-term mechanical properties at recycled contents up to 30 wt%. However, such results are limited to short-term testing and do not account for the long-term performance requirements of pressure-rated components. Recent research has shown that the mechanical behaviour of recycled polyolefins is strongly affected by polymeric and non-polymeric impurities, which may substantially reduce slow crack growth resistance and promote premature failure under sustained loads (Messiha et al., 2025). Because these impurity-related effects are not captured by standard short-term tensile or impact tests, long-term assessment methods are

required to reliably evaluate durability. Consequently, current ISO, EN and ASTM standards do not permit the use of rHDPE in pressure-pipe fittings, and its potential application in marine environments remains subject to stringent quality control and comprehensive long-term verification. Nevertheless, as an initial screening step, short-term mechanical tests are useful to determine whether deeper long-term investigations on rHDPE are justified.

In addition to material selection, the construction methodology plays a critical role in determining the structural integrity and long-term performance of HDPE-based vessels. A widely adopted approach in HDPE boatbuilding involves the thermal welding of single-skin panels, which ensures watertightness and mechanical continuity across hull and superstructure components (Niou et al., 2018). Two principal techniques are commonly employed: machine-based fusion welding and extrusion welding. Machine-based fusion welding—typically executed by hot plate systems—relies on the controlled application of heat and pressure to the joining surfaces (Novakovic et al., 2023). Once the HDPE interfaces reach the appropriate melting temperature, they are pressed together and allowed to cool under load, forming a homogeneous weld with high mechanical strength. This method is particularly suited for linear joints and large-scale panel assemblies, offering repeatability and precision in industrial settings. Extrusion welding, by contrast, is a more versatile technique, commonly employed for complex geometries, fillet joints between longitudinal and transverse structural members, connections between beam or girder webs and hull plating, as well as for field repairs (Lee, 2023). It involves the localized melting of HDPE filler material, which is deposited between the joint surfaces using a handheld extrusion device. The process includes preheating the weld zone, plasticizing the filler rod, and applying it through a shaped die to achieve a continuous bond. While extrusion welding allows for greater adaptability, its success depends heavily on operator skill and process control, as weld quality can be affected by temperature fluctuations, contamination, and uneven deposition.

Assessing the quality of thermal welding in HDPE vessels is paramount to ensuring structural integrity, long-term performance, and environmental resilience, particularly in marine and industrial applications. Indeed, among the various joining methods explored—including bolting, adhesive bonding, and welding—welding has often emerged as the least reliable in terms of strain distribution and failure modes (Sözen et al., 2022).

The present study introduces several original contributions to the assessment of HDPE for marine structural applications. First, it presents a unified experimental comparison of virgin, recycled, and welded HDPE, addressing both base material behaviour and joint performance within a framework directly relevant to elastic structural design. Second, the mechanical performance of butt-welded joints produced by machine-based fusion and manual extrusion welding is evaluated using consistent specimen geometries, enabling a direct comparison between industrial and field-applicable joining techniques commonly employed in HDPE boatbuilding. Third, the study integrates mechanical testing with Digital Image Correlation (DIC), Infrared Thermography (IRT)—previously applied by some of the authors for the investigation of welded joints (Crupi et al., 2007, Crupi et al., 2009, Crupi et al., 2010)—and Fourier-transform infrared (FT-IR) spectroscopy to establish clear links between global mechanical response, strain localization, damage initiation, and chemical structure. Finally, the experimental results are explicitly benchmarked against the requirements of major ship classification societies, providing regulatory insight that is seldom addressed in existing literature and directly supporting the structural qualification of HDPE assemblies for marine applications. This combination of material characterisation, advanced full-field measurement techniques, and regulatory analysis addresses a gap in the existing literature and provides a directly applicable contribution to the structural qualification of HDPE assemblies for marine applications, within a normative framework that is currently evolving to accommodate sustainable and alternative hull materials.



Fig. 1. HDPE workboat (<https://workboat365.com/wp-content/uploads/2023/11/6.webp>).

2. Materials and methods

2.1. Materials

2.1.1. HDPE mechanical properties

Virgin HDPE (v-HDPE) is characterised by consistent mechanical performance and high purity, whereas r-HDPE, derived from post-consumer or post-industrial sources, may exhibit slight property variations due to thermal and oxidative degradation during reprocessing. [Table 1](#) summarises the nominal mechanical properties provided by the material suppliers for both the virgin and recycled HDPE used in this study ([G.B. Plast Srl n.d.](#), [Boianoflon Srl n.d.](#)). For the recycled material, the percentage of regenerated HDPE in the blend, as well as the nature and content of any polymeric or non-polymeric impurities or additives, were not disclosed by the supplier for commercial confidentiality reasons. Based on the mechanical properties reported in the technical datasheet and their similarity to those of the virgin material, it can be inferred that the recycled content is unlikely to exceed the range investigated by [Tesfaw et al. \(2022\)](#) for short-term mechanical performance. However, it must be acknowledged that short-term mechanical properties alone are not sufficient to exclude the presence of impurities that may adversely affect long-term structural performance, including slow crack growth resistance, as documented in recent literature ([Messiha et al., 2025](#)). This constitutes an explicit limitation of the present study, and the conclusions drawn are strictly referred to the short-term mechanical response of the material as supplied.

With specific reference to RINA Rules, it is important to note that the use of r-HDPE is currently not permitted for structural applications. This regulatory limitation represents one of the drivers of the present research, which aims to deepen the understanding of mechanical properties of r-HDPE.

2.1.2. Welding requirements for HDPE boatbuilding applications

In the context of vessel construction, the welding provisions issued by RINA, BV, and IRS share a common goal: guaranteeing the structural integrity of HDPE hulls under marine operating conditions ([Registro Italiano Navale, 2023](#), [RINA, 2023](#), [Bureau Veritas, 2022](#), [Indian Register of Shipping, 2024](#)). These standards reflect the unique behaviour of thermoplastics under thermal and mechanical loads. All three frameworks require that critical joints—such as those in the bottom, keel, side shell, and strength deck—be executed as butt welds with full penetration from both sides, ensuring efficient load transfer and fatigue resistance. Fillet welds are generally permitted only when double

continuous and with a throat thickness not less than that of the thinner plate in the assembly, reflecting a consistent approach to joint geometry across BV, RINA, and IRS.

Documentation requirements are also aligned: when structural drawings do not provide complete welding details, BV and RINA mandate the submission of a welding booklet, while IRS requires a Welding Procedure Specification (WPS). These documents typically include joint design, welding procedures, inspection protocols, and repair strategies, serving as a technical reference for surveyors and ensuring traceability of welding operations. However, the verification approach differs significantly. BV enforces mechanical performance testing of welded specimens according to ISO EN 12814 – Part 2, requiring joints to achieve at least 80% of the base material's breaking stress and explicitly accounting for a 20% reduction in strength within the heat-affected zone. RINA, by contrast, emphasizes non-destructive testing (NDT), leaving the definition of extent and acceptance criteria to the shipyard, while requiring systematic documentation of results. IRS combines both philosophies, mandating mechanical tests and a comprehensive suite of NDT methods—including visual, radiographic, ultrasonic, and high-voltage inspections—supported by defect classification and quality level standards.

Differences also emerge in the integration of welding requirements with broader quality control measures. IRS provides the most extensive framework, embedding welding provisions within a detailed manufacturing process that includes welder qualification per EN 13067, internal quality control (recording process parameters, visual inspection of welds, periodic thickness checks), and strict compliance with international standards such as EN 12814 and EN 13100. BV and RINA, while requiring qualified welders and documented procedures, do not prescribe the same level of process traceability. Material-related constraints further distinguish the rules: RINA explicitly prohibits the use of r-HDPE for structural members, citing concerns over weldability and strength consistency, whereas BV and IRS allow flexibility provided that material properties are verified and documented.

In summary, BV, RINA, and IRS converge on essential principles—qualified welding procedures, strict joint geometry, and robust inspection regimes—while differing in their emphasis on mechanical versus NDT, the depth of process control, and the treatment of material sourcing. Together, these provisions define a technically rigorous and safety-oriented approach to welding requirements for HDPE boatbuilding applications.

Table 1
Mechanical properties of virgin and recycled HDPE ([G.B. Plast Srl n.d.](#), [Boianoflon Srl n.d.](#)).

	Value		
	Test method	Virgin	Recycled
General properties			
Density [g/cm ³]	DIN EN ISO 1183-1	0.95	>0.93
Water absorption [%]	DIN EN ISO 62	<0.01	<0.01
Mechanical properties			
Yield stress [MPa]	DIN EN ISO 527	22	>20
Elongation at break [%]	DIN EN ISO 527	>50	-
Modulus of elasticity [MPa]	DIN EN ISO 527	800	>800
Shore hardness D	DIN EN ISO 868	63	60÷63
Thermal properties			
Melting temperature [°C]	ISO 11357-3	135	135
Thermal conductivity [W/mK]	DIN 52612-1 / ISO 52612	0.40	0.40
Coefficient of linear thermal expansion [10 ⁻⁶ /K]	DIN 53752 / ISO 11359-2	+150 ÷ +230	+200
Service temperature – long term [°C]	- (supplier data)*	-50 ÷ +80	-100 / +80
Service temperature – short term [°C]	- (supplier data)*	+100	+100
UL 94 Flammability (thickness 3-6 mm) (Underwriters Laboratories, 2013)	UL 94	HB	HB

* Service temperatures are reported as provided by the material suppliers in the respective technical datasheets; no standardised test method or test duration was specified for their determination.

2.1.3. Welding procedures for HDPE panels

This section outlines the welding procedures adopted for joining HDPE panels, as they represent a critical aspect of the experimental setup and influence the mechanical performance evaluated in the study. Specifically, two welding methods were employed: butt fusion welding and extrusion.

Butt fusion welding of panels involves a four-stage thermal joining process using a heated tool (usually a metal hot plate) to generate an entangled polymer interphase between the planar components (Novakovic et al., 2023, Alhatti et al., 2025). The procedure is anticipated by a preparation phase in which the HDPE panel ends are clamped securely in the machine's holding units and a facing tool (planer) is used to machine the ends of the components to ensure they are flat, smooth, and perpendicular to the axis. After facing, the components are brought together to check for alignment and gap, and any misalignment is corrected before proceeding. Then, the process starts with the bead-up stage that aims to ensure full surface contact between the HDPE panels and the hot plate. In this phase, heat transfer is deliberately withheld, and mechanical pressure alone is applied to ensure surface conformity to the hot plate geometry and eliminate irregularities and any displaced material. The bead-up is followed by the heating stage, in which the metal hot plate is heated (typically at 210–230°C) and the pressure is reduced for a heat soak period, allowing the melt layer to develop to the required depth. Subsequently, the changeover stage entails rapid retraction of the heated plate and the alignment of HDPE panels for joining. Here, the molten surfaces are brought together under controlled pressure and allowed to cool during the last cooling phase. The process is sensitive to surface area and thermal expansion effects, necessitating precise control of equipment and conditions to ensure consistent bonding performance. Moreover, the predominant parameters governing the butt fusion welding process, namely heater plate temperature, pressure, and time, are influenced by the panel thickness, in accordance with the procedural framework defined in DVS 2207-1, which specifically addresses butt fusion welding of polyethylene panels and sheets and represents the operative welding standard adopted by the machine employed in this study (DVS - German Welding Society, 2007). This is particularly evident in Table 2, which presents the specific process parameters for butt fusion welding of HDPE panels with thicknesses of 10 mm and 15 mm, as recorded directly by the reporting system of the welding machine employed.

It is worth noting that, in accordance with Section 4.1.3 of DVS 2207-1, the heater plate temperature for butt fusion welding of PE-HD panels falls within the range of 200 to 220°C, with higher temperatures recommended for smaller wall thicknesses and lower temperatures for greater wall thicknesses. The recorded values of 214°C for the 10 mm thick panel and 209°C for the 15 mm thick panel are therefore fully

consistent with this thickness-dependent temperature guidance.

Furthermore, in accordance with DVS 2207-1, the joining pressure is defined as an interfacial pressure per unit area of the joint surface, prescribed at 0.15 ± 0.01 N/mm². The gauge pressure applied by the machine cylinders therefore depends on both the required interfacial pressure and the contact surface area of the joint, which is in turn determined by the panel width. Similarly, the bead-up time depends not only on the wall thickness but also on the panel width, as a larger contact surface requires a longer time to achieve full and uniform contact across the entire joint interface. Consequently, panels of different widths require different gauge pressures and bead-up times to achieve the same interfacial pressure and contact quality at the weld interface, as reflected in the values reported in Table 2, where the 10 mm thick panel had a width of 1500 mm and the 15 mm thick panel had a width of 500 mm.

For the purposes of the study, the authors employed a Computer Numerical Control (CNC) automatic welding machine (TECNODUE – SLG 4000 – MAT.0318510 [<https://www.tecnodue.eu/prodotto/slg-4000/>]) suitable for butt welding of plastic panels ensuring a maximum weldable thickness equal to 30 mm (Fig. 2a).

As for extrusion welding, this is a specialized joining technique used for thermoplastics, in which a molten filler material is continuously deposited into a preheated joint to form a cohesive weld. The process involves simultaneously heating the joint surfaces to their softening temperature and melting the filler material within an extruder, which then forces it through a shaped welding shoe to match the geometry of the joint (Lee, 2023). Extrusion welding is widely adopted in HDPE boat construction due to its efficiency in forming reliable welds in thick sections that are commonly used for hull structural components and superstructures (Sözen et al., 2022, Wibawa et al., 2023). This method enables the creation of strong, uniform welds in a single pass, making it particularly effective for thick-section materials such as HDPE panels. In this study, the welding equipment featured a compact and ergonomic design, with the motor mounted at the top and the handle and blower located at the bottom, facilitating ease of use and adaptability across various welding positions (i.e., a LEISTER FUSION 3C extruder [<https://www.leister.com/en/product/Fusion-3C/123-866#TechnicalData>]). The extruder offers multiple sealing configurations to accommodate various welding positions, making it particularly suitable for applications such as boatbuilding (Fig. 2b). It achieved an output rate of up to 3.6 kg/h, enabling consistent material flow during welding. Additionally, a heat gun was employed as a profiling tool for processing plastic membranes and assisting in thermoplastic shaping tasks. Its dual-sided air filters were removable and washable, ensuring optimal airflow and reliable performance throughout the welding process. These equipment characteristics made the setup particularly suitable for precision welding in marine-grade HDPE panel fabrication.

Table 2

Welding parameters for 10- and 15-mm thick panels, as recorded by the welding machine reporting system in accordance with DVS 2207-1.

	Thickness equal to 10 mm	Thickness equal to 15 mm
Environment temperature [°C]	17	18
Panel width [mm]	1500	500
Starting pressure [bar]	11.7	11.5
	Phase 1 – Bead-up	
Pressure [bar]	29.7	20.7
Time [s]	90	85
	Phase 2 – Heating	
Temperature [°C]	214	209
Pressure [bar]	7.3	7.4
Time [s]	100	150
	Phase 3 – Changeover	
Time [s]	11	12
	Phase 4 – Cooling	
Pressure [bar]	29.5	20.4
Time [s]	816	1165



Fig. 2. Welding devices employed in this study: (a) CNC automatic butt fusion welding machine (TECNODUE SLG 4000); (b) manual extrusion welding device (LEISTER FUSION 3C). Images are reproduced from the respective manufacturer documentation.

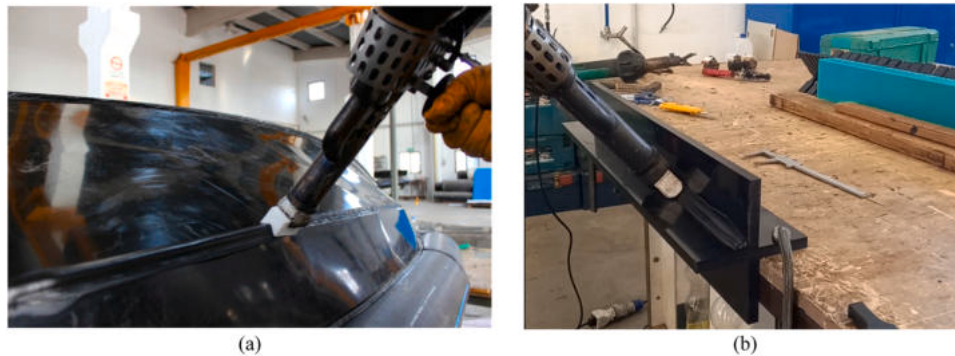


Fig. 3. Extrusion welding: (a) Hull welding (Sözen et al., 2022); (b) Fillet welding on cruciform joint.

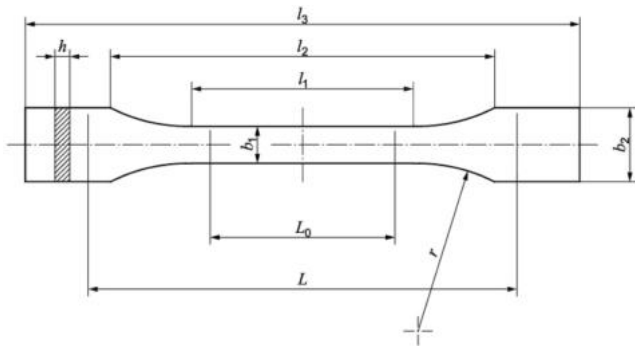


Fig. 4. Dog-bone specimen type for ISO 527-1 standard (ISO 2012).

Extrusion welding offers notable advantages in terms of process flexibility and adaptability to complex geometries frequently encountered in boat hull construction. Because the technique employs a portable, hand-held extruder, it enables operators to perform welds directly on curved or irregular surfaces, making it particularly suitable for assembling hull parts with non-linear profiles (Fig. 3a). Moreover, as most internal structures of a vessel require orthogonal welding within confined spaces to create cruciform joints, the extruder remains the only practical device capable of executing these operations under such spatial constraints (Fig. 3b). In contrast, butt-welding with hot-plate machines typically requires precise alignment of flat or uniformly shaped panels, and the equipment is generally bulkier and less manoeuvrable. This method becomes challenging when applied to curved hull surfaces or confined areas within a boat structure. The rigidity of the setup and the need for clamping and alignment fixtures limit its use in field conditions or on-site repairs. Moreover, extrusion welding allows for continuous material deposition along the joint, which simplifies the welding of thick

HDPE sections and reduces the need for multiple passes. This contributes to faster processing times and lower labour intensity, especially when compared to hot-plate welding, which may require longer heating and cooling cycles and more complex preparation steps.

2.2. Methods

2.2.1. Specimen geometry and manufacturing

In accordance with the requirements established by RINA, the testing procedures adopted in this study followed the guidelines provided by the International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM). Particular attention was given to standards ISO 527-1, “Plastics – Determination of Tensile Properties – Part 1: General Principles,” and ASTM D638-14, “Standard Test Method for Tensile Properties of Plastics,” which specify the determination of tensile properties of plastic materials, including tensile strength, modulus, and stress-strain behaviour (ISO, 2012, American Society for Testing and Materials, 2016). The geometries of the tensile specimens were developed on the basis of ISO 527-1 standard (Fig. 4), which served as the primary reference for specimen geometry definition, while ASTM D638 was consulted as a complementary reference for the general testing procedure. Several practical constraints related to the testing procedure and the limitations of the equipment employed were also taken into account (Taucer Marchesi et al., 2025). Specifically, modifications were introduced to the overall specimen length to accommodate the maximum separation capacity of the testing machine grips. As a consequence, the fillet radius and the gauge length were proportionally adjusted according to the geometry of the gripping sections. The contact surfaces were prepared with abrasive paper to ensure proper grip engagement. In addition, all specimens were manufactured with a minimum square cross-section to ensure consistent alignment and to simplify the comparison among the different material configurations. The study focused on dog-bone specimens manufactured from

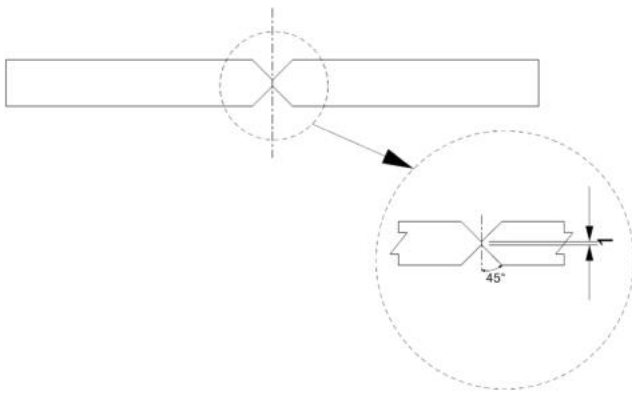


Fig. 5. Chamfer preparation for extruder-welded dog-bone specimens (dimensions in millimetres).

virgin and recycled HDPE, as well as on butt-welded dog-bone specimens made of v-HDPE, to enable a comparison of weld quality between the two materials (Bertagna et al., 2025, Brando et al., 2025). The specimen thicknesses were determined in accordance with both the dimensions usually employed for the most relevant boat structures (main girders and beams and hull plating) and the commercially available panels adopted for marine applications. As a result, the specimens were manufactured with panels having thicknesses equal to 10 and 15 mm.

The manufacturing process varied depending on the type of specimen. For simple dog-bone specimens, no preliminary processing was required prior to CNC cutting. The procedure consisted solely of positioning the HDPE panel of the selected thickness (10 mm or 15 mm) inside the CNC machine, which had been supplied with an input file exported directly from the parametric design software containing the exact geometry of the required specimen.

For butt-welded specimens produced using the TECNODUE CNC welding machine, no preprocessing of the panels was necessary. Only upon completion of the welding operation was the excess weld bead removed prior to cutting the specimens with the CNC machine. The weld bead was removed prior to specimen cutting in accordance with EN 12814, Section 6, which prescribes that the weld bead condition of the test specimen shall replicate the in-service condition (EN n.d.). In HDPE vessel construction, the weld bead is systematically removed from the external hull plating to ensure a smooth hydrodynamic surface, and the specimen preparation adopted in this study therefore reflects the actual service condition of the structural components examined. In fact, neither RINA nor Bureau Veritas explicitly prohibit the removal of the weld bead in their respective rules for HDPE hull construction, and Bureau Veritas references EN 12814 as the applicable standard for mechanical qualification testing of welded assemblies.

In contrast, the fabrication of dog-bone specimens welded using an extruder required an initial preparation step. Each specimen consists of two separate HDPE panels joined by extrusion welding. Prior to welding, a 45° chamfer was machined on both faces of each panel at the joining end, leaving approximately 1 mm of intact material at the mid-thickness

(Fig. 5) so as to form a double-V groove joint configuration as described in Wibawa et al. (2023). The extrusion weld was then applied manually into this groove, first on one side and subsequently on the other, creating a continuous bond between the two panels. After welding, the specimens were cut to their final geometry using the CNC machine. It is noted that the general dog-bone geometry of all specimens is consistent with that described in Taucer Marchesi et al. (2025). The 45° chamfer illustrated in Fig. 5 represents a local preparation of the weld zone specific to the extrusion welding procedure, and does not constitute a modification of the overall specimen geometry. It is acknowledged that the dog-bone specimen geometry adopted in this study does not guarantee failure initiation at the weld zone, as necking may develop at any weaker point within the gauge length. The waisted specimen geometry prescribed in ISO 13953 (ISO, 2001), which ensures consistent failure at the weld location, was not employed in the present study and is identified as an important methodological development for future investigations aimed at a more targeted characterisation of weld quality and failure behaviour.

Finally, all specimen types underwent manual surface preparation at their ends. A roughened area approximately 40 mm in length was created by using abrasive paper to prevent slippage during clamping in the testing machine.

Each specimen was assigned a unique alphanumeric code that encoded key information, including the material type (virgin or recycled), the loading condition (tensile), the thickness t , and any specific characteristics of the specimen. The meaning of each code component is detailed in Table 3. Additionally, specimens were sequentially numbered to facilitate accurate tracking and data collection.

2.2.2. Testing procedures

In accordance with Standards ISO 527 e ASTM D638 (ISO, 2012, American Society for Testing and Materials, 2016), the testing procedure involved extending the specimen along its main longitudinal axis at a constant rate until fracture occurs or until a predetermined value of stress (load) or strain (elongation) is reached. During the test, both the load sustained by the specimen and the corresponding elongation are continuously recorded.

Tensile tests were carried out at 10 mm/min cross-head speed using an Italsigma FPF 25 servo-hydraulic testing machine equipped with a 25 kN load cell, calibrated according to ISO 7500-1 (Class 1) (ISO, 2004). Testing was performed under controlled laboratory conditions, with a temperature of $23 \pm 2^\circ\text{C}$ and a relative humidity of $50 \pm 10\%$. The experimental setup combined DIC and IRT techniques, which were applied simultaneously during the tests. DIC measurements were performed with the open source 2D software Ncorr v1.2 (Blaber et al., 2015) to determine strain fields during tensile loading. A random speckle pattern was created on the specimen surface using gel coat spray, and images were acquired with a super-macro lens at a resolution of 1280×720 pixels and a frame rate of 60 fps. Calibration, based on specimen dimensions, yielded spatial resolutions of 0.18 mm/pixel. Surface temperature was monitored with a FLIR SC640 infrared camera with a resolution of 640×480 pixels. To ensure proper emissivity for IRT, the opposite specimen surface was coated with black paint.

Table 3
Specimens' characteristics.

	VT15S	RT10S	VT10BWM	VT15BWM	VT10BWE	VT15BWE
Material						
Thickness [mm]	15	10	10	15	10	15
Description	Simple dog-bone	Simple dog-bone	Butt fusion Welding Machine	Butt fusion Welding Machine	Butt Welding with Extruder	Butt Welding with Extruder

Thermal images were collected at 3.75 fps and processed with FLIR ResearchIR Max software. FT-IR analyses were recorded using a Fourier-transform infrared (FT-IR) Spectrum Two Spectrometer (PerkinElmer Inc., Waltham, MA, USA), by the ATR method in the range of 4000–500 cm^{-1} . Thermogravimetric analysis (TGA) was carried out on four HDPE samples using a PerkinElmer TGA 4000 (PerkinElmer Inc., Waltham, MA, USA). Approximately 10 mg of each sample were heated from 25 to 550°C at 10°C min^{-1} under an argon flow of 20 mL min^{-1} , with measurements performed in triplicate.

2.2.3. Statistical analysis

Mean values ($\bar{x}$) and sample standard deviations (s) were computed for both tensile strength—defined at the yield point in accordance with the relevant classification society Rules and hereafter referred to as maximum stress—and Young's modulus, with both quantities derived from the force–displacement data obtained during testing. For Young's modulus, a linear regression analysis was performed on the initial portion of the curve (within the range $0.10 \div 0.40 F_{max}$, where F_{max} is the maximum load recorded during the test). Within this interval, a sub-region was selected to obtain a regression line with a coefficient of determination R^2 greater than 0.99. It is noted that the modulus determination procedure adopted in this study differs from the strain-based approach prescribed by ISO 527-2 (0.05% to 0.25% strain range). The load-based approach employed here (0.10 to 0.40 F_{max}) ensures that all measurements are performed well within the accurate range of the load cell, with minimum load values at the lower bound of the regression interval exceeding 315 N for the 10 mm thick specimens and 450 N for the 15 mm thick specimens, both substantially above the 100 N accuracy threshold of the 25 kN load cell. It is further noted that even at a strain of 0.05%, the minimum load measured by the load cell varies in the range of 400 to 600 N across all specimens, confirming that all measurements fall within the accurate range of the load cell.

To account for the dispersion of the experimental data, characteristic threshold values x_k were determined. These values correspond to the 5th percentile, representing a lower bound exceeded by 95% of the population. Assuming a normal distribution of the data, the 5th-percentile value was calculated according to the following expression: $x_k = \bar{x} - 1.645s$.

3. Results and discussion

3.1. Statistical analysis on mechanical properties and failure modes

The strain during the tensile tests was evaluated using the Digital Image Correlation (DIC) technique, considering the displacement Δl relative to a reference length l_0 of 50 mm within the specimen's gauge section, as shown in Fig. 6. As the testing machine presents a maximum stroke of 100 mm, the specimens that did not exhibit fracture were tested up to this limit.

A total of seven specimens were tested for the unwelded virgin HDPE

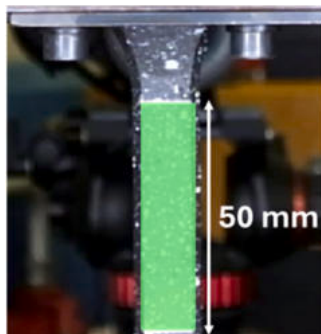


Fig. 6. Reference length for engineering strain evaluation during the tensile tests.

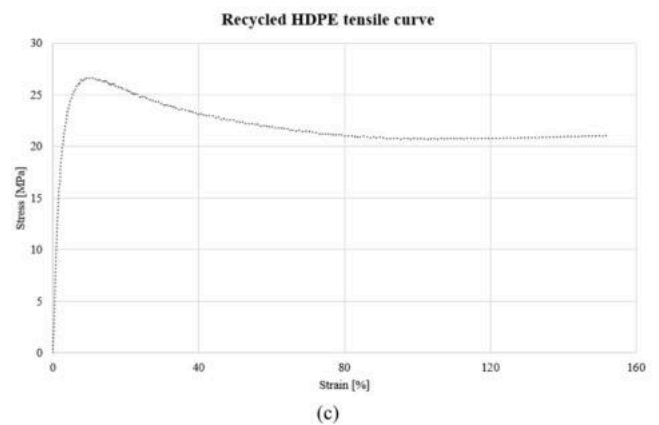
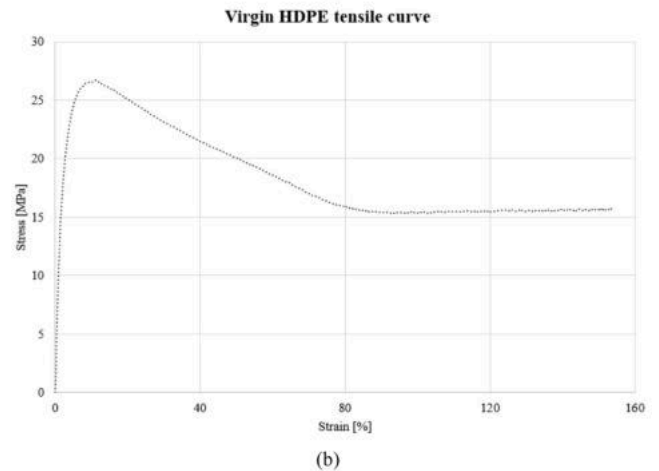
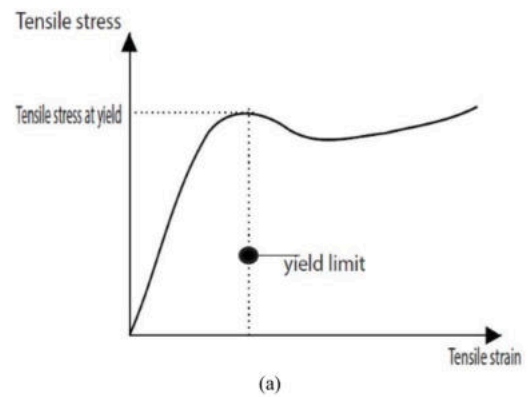


Fig. 7. Stress-strain curve of HDPE as reported in Rules: (a) RINA (Registro Italiano Navale 2023); (b) virgin specimens VT15S_2; (c) recycled specimens RT10S_2.

configuration with a thickness of 15 mm (VT15S), while eight specimens were tested for each of the remaining configurations, for a total of 55 specimens across all material and welding configurations examined. For all specimens tested, stress–strain curves were obtained and collected (representative curves of the non-welded specimens are shown in Fig. 7). It is noted that all stress–strain curves presented in this study are engineering stress–engineering strain curves, in which stress is calculated with reference to the original cross-sectional area of the specimen and strain is referred to the original gauge length. The complete set of curves is reported in Bertagna et al. (2025) and Brando et al. (2025). On the other hand, with reference to Fig. 7a, this Fig. illustrates the typical stress–strain response of HDPE as presented by RINA; it does not constitute a prescriptive requirement of the Rules but is included solely for qualitative and illustrative purposes, to facilitate comparison

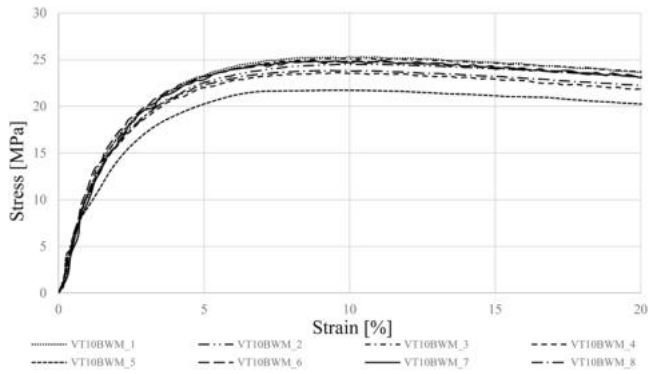


Fig. 8. Stress-strain curves for virgin HDPE VT10BWM specimens up to strain equal to 20%.

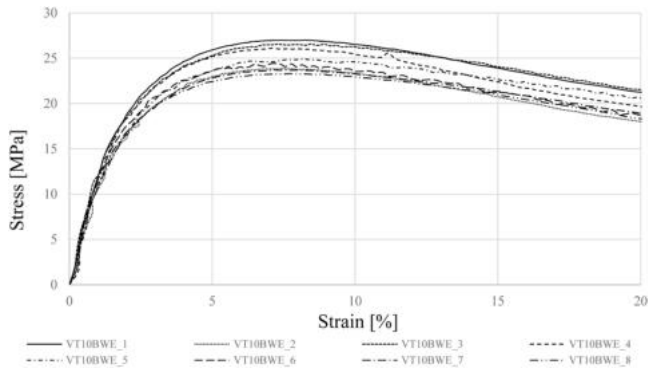


Fig. 9. Stress-strain curves for virgin HDPE VT10BWE specimens up to strain equal to 20%.

between the shape of the experimental curves and the idealised material response assumed in structural design. For v-HDPE specimens (Fig. 7b), these initially exhibit a linear elastic deformation up to the elastic limit where non-linear deformation occurs. The stress rises, eventually reaching the yield stress followed by the strain-softening region characterised by a sharp load drop up to a plateau region at constant stress. On the other hand, r-HDPE samples (Fig. 7c) show a similar behaviour as the virgin specimens up to the yield stress. However, in the strain softening region the load gradually decreases, with no sharply defined boundary separating it from the plateau region.

In the present paper, two representative set of curves were selected to illustrate the overall experimental results. Specifically, Figs. 8 and 9 present the stress-strain curves for the following configurations of 10-mm thick virgin HDPE butt-welded specimens: welded using either a welding machine (Fig. 8) or an extruder (Fig. 9). In accordance with elastic structural design principles based on the knowledge of the yield stress, the analysis focuses on the portion of the curve up to a strain of 20%, which is sufficient to capture the elastic response and the onset of plastic deformation while remaining relevant for structural design applications. Based on these curves, a statistical analysis was performed for each type of specimen, as described in Section 2.2.3, in order to quantify the variability and representative mechanical parameters. The corresponding results are reported in Table 4.

The values reported in Table 4 provide a clear and quantitative confirmation that the yield stress and Young's modulus of the r-HDPE (RT10S) are comparable to those of the v-HDPE (VT15S). Both materials very similar mean yield stress values (24.7 MPa and 24.3 MPa), although individual specimens span wider ranges. Their Young's moduli are likewise similar, with mean values of 943 MPa and 958 MPa, demonstrating that the recycling process does not induce any measurable degradation in the material stiffness or yield stress, within the scope of the quasi-static tensile tests performed. A broader comparison with the welded configurations further highlights the influence of the joining technique. Extrusion-welded specimens (VT10BWE and VT15BWE) display the highest material stiffness among all welded groups, with

Table 4

Results of the statistical analysis obtained for all the tested specimens.

VT15S (Virgin HDPE, thickness equal to 15 mm, Simple non-welded specimen)												
Specimen	1	2	3	4	5	6	7		Mean value	Standard deviation	Standard error	x _k
Max stress [MPa]	21	27	26	26	26	25	22		24.7	2.3	±0.87	20.9
Young's modulus [MPa]	908	990	937	947	1064	852	905		943	68.1	±25.8	831
RT10S (Recycled HDPE, thickness equal to 10 mm, Simple non-welded specimen)												
Specimen	1	2	3	4	5	6	7	8	Mean value	Standard deviation	Standard error	x _k
Max stress [MPa]	23	27	27	24	23	23	24	23	24.3	1.8	±0.62	21.3
Young's modulus [MPa]	975	966	964	992	915	930	997	922	958	31.6	±11.2	906
VT10BWM (Virgin HDPE, thickness equal to 10 mm, Butt fusion Welding Machine)												
Specimen	1	2	3	4	5	6	7	8	Mean value	Standard deviation	Standard error	x _k
Max stress [MPa]	25	24	25	24	22	25	25	24	24.3	1.1	±0.37	22.5
Young's modulus [MPa]	1052	1077	1031	976	1002	1143	1006	1015	1038	52.8	±18.7	951
VT15BWM (Virgin HDPE, thickness equal to 15 mm, Butt fusion Welding Machine)												
Specimen	1	2	3	4	5	6	7	8	Mean value	Standard deviation	Standard error	x _k
Max stress [MPa]	24	23	26	22	23	23	24	24	23.6	1.2	±0.42	21.6
Young's modulus [MPa]	1040	854	994	926	863	959	891	921	931	64.3	±22.7	825
VT10BWE (Virgin HDPE, thickness equal to 10 mm, Butt Welding with Extruder)												
Specimen	1	2	3	4	5	6	7	8	Mean value	Standard deviation	Standard error	x _k
Max stress [MPa]	27	24	27	26	25	24	24	23	25.0	1.5	±0.54	22.5
Young's modulus [MPa]	1120	949	1218	1141	1098	1116	1126	1180	1119	78.7	±27.8	990
VT15BWE (Virgin HDPE, thickness equal to 15 mm, Butt Welding with Extruder)												
Specimen	1	2	3	4	5	6	7	8	Mean value	Standard deviation	Standard error	x _k
Max stress [MPa]	26	27	23	25	25	26	25	25	25.3	1.2	±0.41	23.3
Young's modulus [MPa]	975	1098	1052	1069	1062	1090	1018	1115	1060	45.5	±16.1	985

Young's modulus values ranging from approximately 949 to 1218 MPa, clearly outperforming both the machine-welded joints (VT10BWM and VT15BWM, 854–1143 MPa) and the simple, non-welded specimens. Despite this variation, all welded configurations maintain maximum stress values on the order of 22–27 MPa, comparable to those of the base materials. This demonstrates that both welding processes—extrusion and machine fusion—preserve the material's yield stress, while extrusion welding can even enhance the effective stiffness of the joint, as reflected in the higher Young's modulus measured in the welded region. The higher Young's modulus observed in extrusion-welded specimens compared to both machine-welded and non-welded configurations may be attributed to a combination of factors. First, the filler rod employed in the extrusion welding process (Polystone® G HD, Röchling Industrial (Röchling Industrial n.d.)) is a virgin HDPE with a declared tensile modulus of elasticity exceeding 1000 MPa, which is nominally higher than the 800 MPa of the base panel material. The contribution of this stiffer filler material to the overall stiffness of the welded region may therefore partly explain the higher Young's modulus measured in the BWE specimens. Second, the mechanical action of the extruder may increase the degree of entanglement at the molecular interphase, resulting in a locally stiffer polymer network and thus contributing to the higher modulus observed in the welded zone. The DIC strain field measurements further support this interpretation, showing lower local strain values in the weld region of BWE specimens under equivalent loading, consistent with a locally stiffer material response.

The expected mechanical properties of HDPE provided in the Rules issued by the Classification Societies RINA, BV, and IRS were examined in this study (Registro Italiano Navale, 2023, Bureau Veritas, 2022, Indian Register of Shipping, 2024). Specifically, both RINA and BV account for the non-linear behaviour of the material and describe a comparable qualitative trend for the HDPE stress–strain curve, as shown in Fig. 7a (the example reported derives from the RINA Rules). It is important to note that, while the stress–strain curves provided by RINA and BV serve as a reference for structural design, they do not exactly match the experimental curves obtained from the experimental tests. As illustrated in Figs. 7b and 7c, representing v-HDPE and r-HDPE respectively, the curves exhibit a similar initial trend corresponding to the linear-elastic region, confirming that the maximum tensile stress measured during testing corresponds to the yield limit defined by the Rules. Beyond this point, the experimental curves—evaluated up to a strain of 160%—are characterised by a horizontal plateau region of approximately constant stress, which can be associated with the so-called natural drawing regime, characterised by the natural draw ratio (NDR). The magnitude of the NDR is known to depend on molecular parameters such as molecular weight and comonomer content (Deveci et al., 2018). Considering the full tensile curve up to failure, Niou et al. (2018) show that after strains of about 300%, the curve develops a new rising segment corresponding to the so-called strain hardening regime, whose slope is known to depend on molecular parameters such as molecular weight, molecular weight distribution, and entanglement density (Deveci and Fang, 2017). This portion displays a quasi-linear trend with a slope different from that of the elastic region, accompanied by increasing stress and strain, with failure occurring at strain values between 500% and 600%. On the other hand, the curves reported by RINA and BV Rules do not clearly show the above-mentioned horizontal plateau; instead, they continue rising beyond the yield point, suggesting a more idealised or simplified

depiction of the overall material response that incorporates both the natural drawing and strain hardening regimes without distinguishing them explicitly. However, it must be noted that structural design principles are based on the mechanical properties of the material up to the yield point. Since the yielding stress obtained from the experimental tests coincides with the values prescribed by the Rules (Table 5), these values can be reliably used for scantling procedures in accordance with the current requirements of RINA and BV. In this regard, the current RINA Rules for HDPE hull structures of workboats (RES 27, Ch 5 (RINA, 2025)) prescribe scantling formulae calibrated on the yield-point mechanical characteristics of the material, namely the tensile modulus of elasticity (E), the tensile stress at yield, and the shear stress at yield. The maximum allowable design stress is defined as a fraction of the tensile stress at yield, with safety coefficients ranging from 1.45 to 1.95 depending on the structural member type and load condition, while hull girder yielding checks impose an upper bound of 70% of the tensile stress at yield on the bending longitudinal stress.

It is acknowledged, however, that HDPE is a viscoelastic material whose mechanical properties are dependent on both temperature and time-dependent loading history. The quasi-static modulus determined from short-term tensile tests is significantly higher than the creep modulus at design lifetime, which may be as low as 30% of the short-term value under sustained loading conditions. It is worth noting in this regard that the typical operating temperatures of HDPE vessels in service are generally well below the long-term service temperature upper limit prescribed by the Rules (i.e., 80°C); furthermore, the materials employed are consistently compliant in terms of maximum service temperature as reported in the material technical datasheet (Table 1). This partially mitigates the practical impact of the temperature-dependent stiffness degradation on in-service structural performance. Nevertheless, the integration of viscoelastic behaviour and creep modulus into structural design procedures for HDPE vessels represents an important direction for future development of both research and classification society frameworks (Liu et al., 2008, Nitta and Maeda, 2010, Shahin et al., 2020, Deveci et al., 2024). It is further noted that the current RINA Rules for HDPE hull structures do not explicitly include fracture toughness or fatigue properties as mandatory structural design parameters. The extension of this elastic, yield-based framework to incorporate fracture mechanics, fatigue-based design criteria, and viscoelastic constitutive modelling represents an important direction for future research and regulatory development.

In the mechanical characterization of the welded specimens, particular attention was devoted to the failure phenomena occurring at the weld interface, where the presence of the joint—and any associated heterogeneities—may critically influence the structural integrity under tensile loading. In fact, none of the non-welded specimens reached

Table 6
Failure mode of the welded specimens.

	1	2	3	4	5	6	7	8
VT10BWM	FE	NO	NO	NO	NO	NO	NO	NO
VT15BWM	FE	MD	FE	NO	NO	FE	FE	FE
VT10BWE	NO	NO	NO	NO	NO	NO	NO	NO
VT15BWE	NO	NO	NO	CF	CF	NO	CF	NO

*FE=fibril elongation, MD= micro ductility, CF=cohesive failure, NO=no fracture intersecting the welded area.

Table 5

Comparison among the test results and the values provided by the Classification Societies (Registro Italiano Navale 2023, Bureau Veritas 2022, Indian Register of Shipping 2024).

	Test results						Classification Societies		
	VT15S	RT10S	VT10BWM	VT15BWM	VT10BWE	VT15BWE	RINA	BV	IRS
Average max stress [MPa]	24.7±0.87	24.3±0.62	24.3±0.37	23.6±0.42	25.0±0.54	25.3±0.41	22	24	>17
Average Young's modulus [MPa]	943±25.8	958±11.2	1038±18.7	931±22.7	1119±27.8	1060±16.1	950	950	-

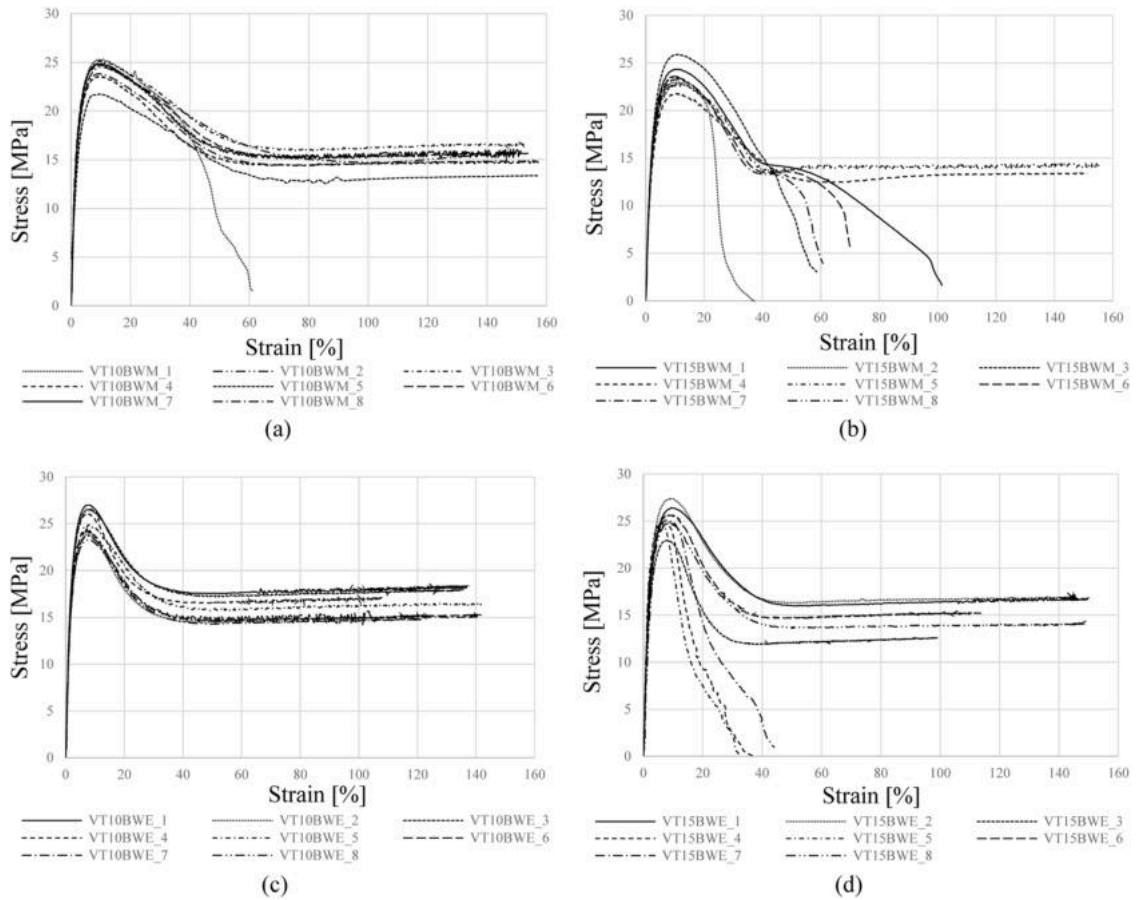


Fig. 10. Stress-strain curves of welded HDPE specimens: (a) VT10BWM; (b) VT15BWM; (c) VT10BWE; (d) VT15BWE.

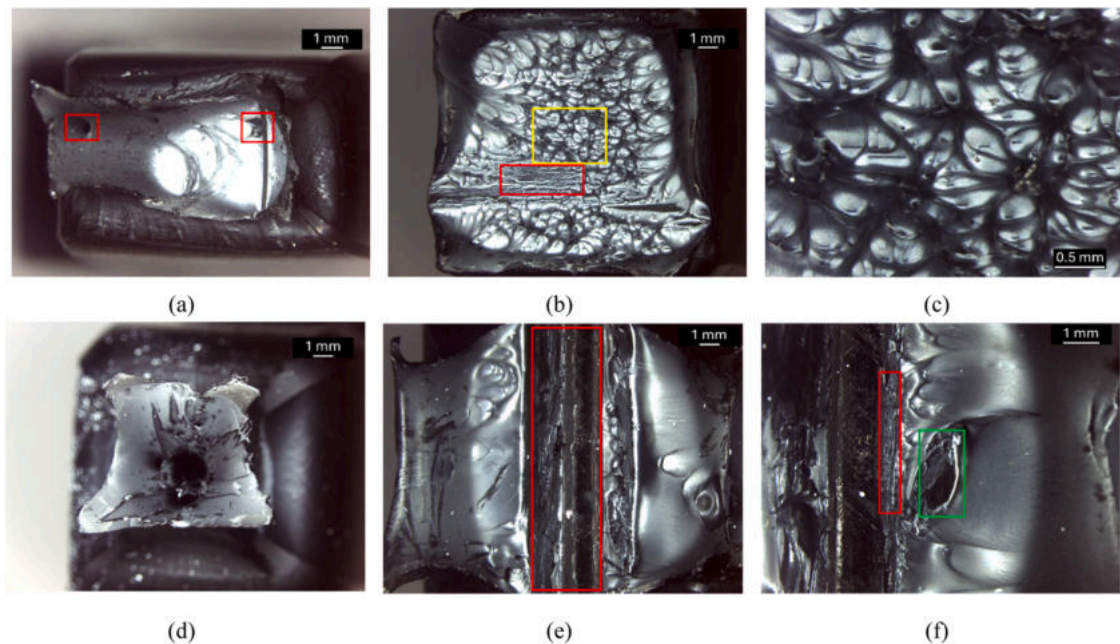


Fig. 11. Optical microscope images: (a) VT10BWM_1; (b) VT15BWM_2; (c) magnification of the yellow square to bring out the microcracks of VT15BWM_2; (d) VT15BWM_6; (e) VT15BWE_4; (f) VT15BWE_7.

failure, while the welded specimens exhibited three different failure modes: fibril elongation, micro ductility, cohesive failure, which are summarised in Table 6. Fig. 10 presents the stress-strain curves of the welded specimens. It can be observed that specimens which do not

exhibit fracture show the same deformation mechanism of the non-welded virgin samples (Fig. 7b).

Fig. 11 shows the optical microscope images of the fracture surfaces of VT10BWM_1, VT15BWM_2, VT15BWM_6, VT15BWE_4 and

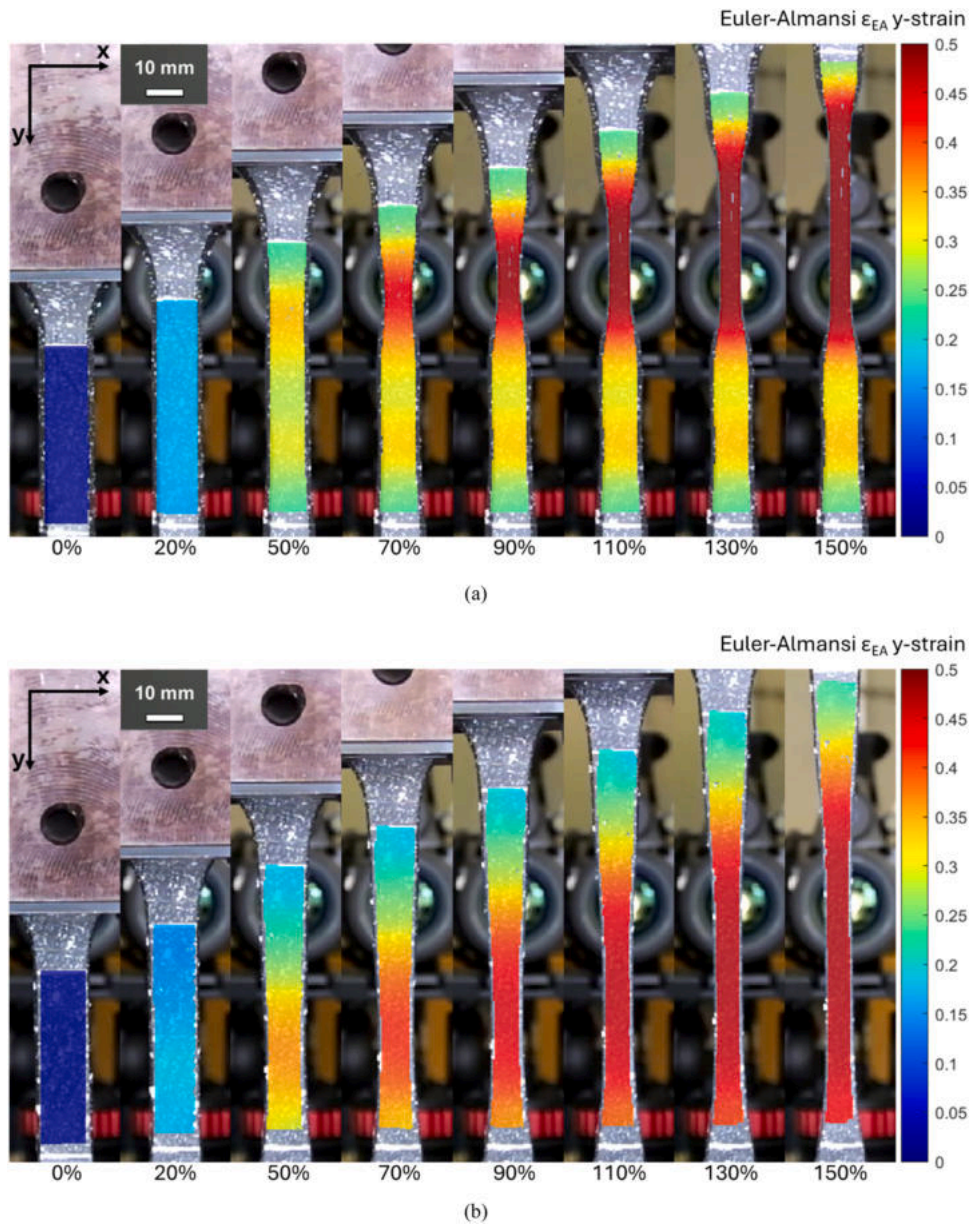


Fig. 12. DIC analysis results of HDPE specimens: (a) VT15S_2 (virgin); (b) RT10S_2 (recycled).

VT15BWE_7 specimens. In the microscopy image shown in Fig. 11a, the presence of inclusions attributable to the welding process can be identified at the fracture surface of the VT10BWM_1 specimen. In this area, the typical failure mode of machine welded specimens with defects of small sizes, characterised by fibril elongation, as reported in Table 6, was detected. Tearing starts from the defects and propagates until failure, as confirmed by the stress-strain curve in Fig. 10a, which shows neither a sharp decrease after the yield stress nor a plateau following strain softening. Fig. 11b reveals the presence of a large area of micro ductility in the fracture surface of the VT15BWM_2 specimen, associated to the carbon black inhomogeneities of the material. An inhomogeneous morphology leads to brittle fracture at the weld interphase, with some amount of micro ductility (Deveci et al., 2019). Moreover, the magnification of the yellow square of Fig. 11b, showed in Fig. 11c, emphasises the development of numerous microcracks concentrated in this area. The micrographs show HDPE spherulites that have cavitated during tensile test. The micro voids form within the spherulites, then grow and coalesce, leaving a bead-like morphology on the fracture surface. Many observations confirm that cavities form when a polymer is stretched, but

not under compression or shear; this phenomenon is referred to as cavitation (Pawlak et al., 2014, Dasari and Misra, 2004). In Fig. 11d, is visible the failure mechanism of the VT15BWM_6 specimen occurred through fibril elongation. The flat zone in the middle of the VT15BWE_4 specimen, highlighted by the red rectangle in Fig. 11e, represents the initiation of the brittle failure which then propagates in the ductile area corresponding to the external region of Fig. 11e. A micro ductility failure mode associated to the carbon black inhomogeneity is also detected for the VT15BWE_7 specimen and highlighted by the red rectangle in Fig. 11f. Moreover, the green rectangle highlights an area associated with the cohesive separation of the weld interface.

3.2. DIC results

Fig. 12a and b show the DIC images of VT15S_2 and RT10S_2 specimens, representative of the two batches. These Fig.s show the DIC images at different engineering strain percentage (Fig. 7), plotting the values of the longitudinal strains, which were evaluated by using the Euler-Almansi algorithm. The strain was evaluated as Eulerian-Almansi

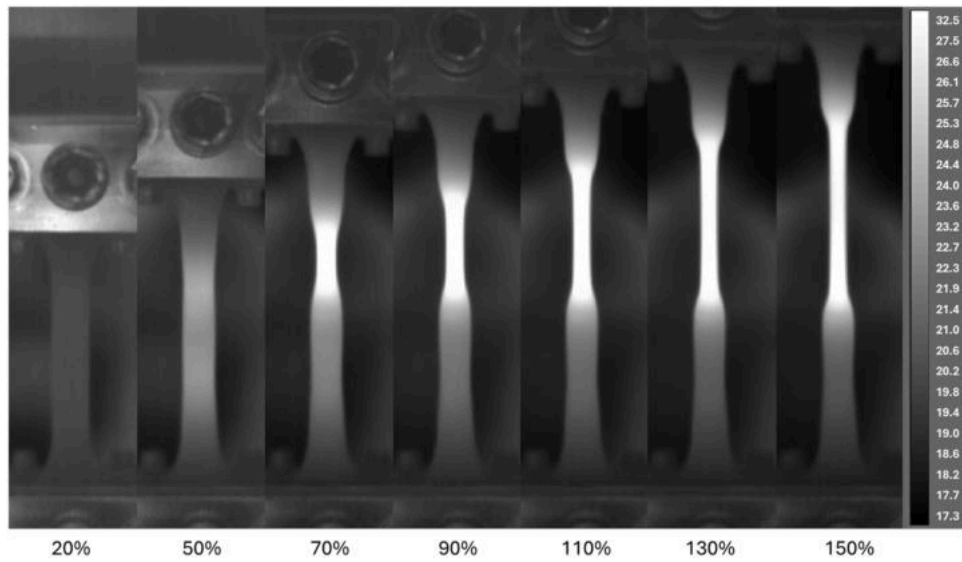


Fig. 13. IRT results of the VT15S_2 (virgin) specimen.

strain defined through Eq. (1) (Gullett et al., 2008).

$$\varepsilon_{EA} = \frac{1}{2} (\mathbf{I} - \mathbf{F}^{-T} \mathbf{F}^{-1}) \quad (1)$$

Where $\mathbf{I}$ is the identity tensor and $\mathbf{F}$ is the deformation gradient. In the case of uniaxial loading the above Eq. reduces to Eq. (2) (Van Mieghem et al., 2016).

$$\varepsilon_{EA} = \frac{1}{2} \left(1 - \frac{1}{\lambda^2} \right) \quad (2)$$

Where λ is the draw ratio defined as the ratio between the instantaneous length l and the reference length l_0 . Euler-Almansi strain acts on the current configuration (Vitzthum et al., 2018). In case of large deformations, different strain tensor algorithms lead to different results. Euler-Almansi is considered an adequate and reliable approach in experimental mechanics, because it portrays the actual physics entailed by measurements (Sciammarella et al., 2019). In the case of uniaxial tensile loading, Eq. (2) shows the ε_{EA} can reach a local maximum value of 0.5.

Necking in PE initiates just after the yield strain ($\sim 10\%$), but becomes clearly visible only at higher strain levels as shown in the VT15S_2 specimen (Fig. 12). The localised deformation subsequently propagating along the entire gauge length of the specimen, as confirmed by the plateau region of the stress-strain curve (Fig. 7b). The RT10S_2

specimen exhibits a different behaviour. Although a reduction in thickness is observed, a pronounced necking region, as observed in the VT15S specimens, does not develop. The deformation propagates almost uniformly along the entire gauge length after the yield stress in the strain softening region and then in the plateau region.

Fig. 13 shows the thermography results for the VT15S_2 (virgin) HDPE specimens. The thermographic images confirm the results obtained through the DIC analyses reported in Fig. 12a. In the VT15S_2 virgin HDPE specimens the increase of maximum temperature is visible starting from 70% strain, with the localised deformation subsequently propagating along the entire gauge length of the specimen.

Infrared thermography was not intended for providing quantitative measurements. Its use was limited to qualitative analysis. Specifically, thermal patterns were correlated with full-field strain distributions obtained via DIC, enabling the identification of localized deformation. The thermographic images in grey scales, shown in the Fig. 13 (virgin) and Fig. 15 (recycled), confirm the results obtained from the DIC analyses reported in Fig. 12a and b for the same specimens. Consequently, the thermographic results are considered in terms of relative variations and spatial-temporal trends, rather than absolute temperature values.

Fig. 14 shows the evolution of the maximum temperature in the necking region as a function of strain for specimen VT15S_2. By correlating this graph with the stress-strain curve, it can be observed that in the initial stage, where the stress increases up to its peak value the

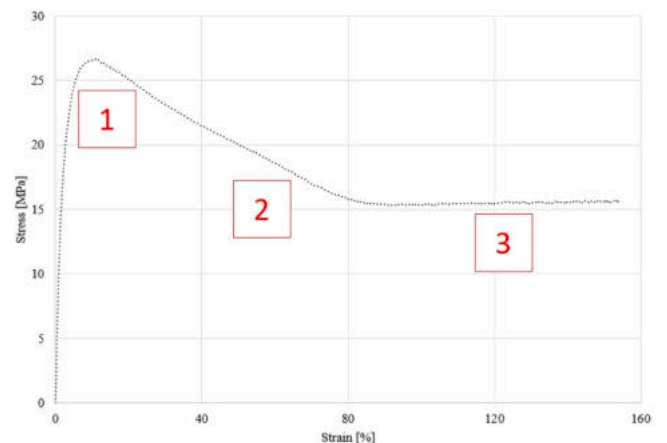
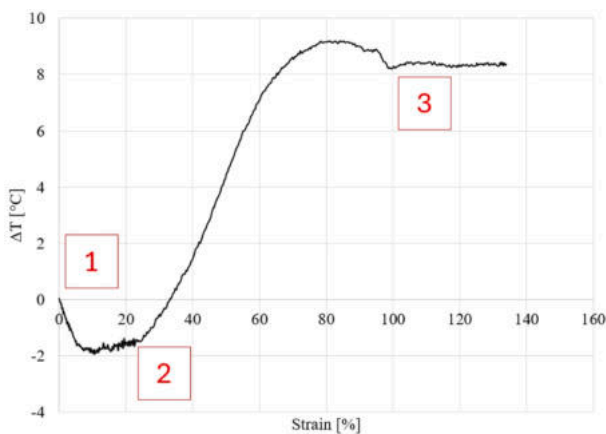


Fig. 14. IRT curve ΔT /Strain and curve Stress/Strain of the VT15S_2 (virgin) specimen.

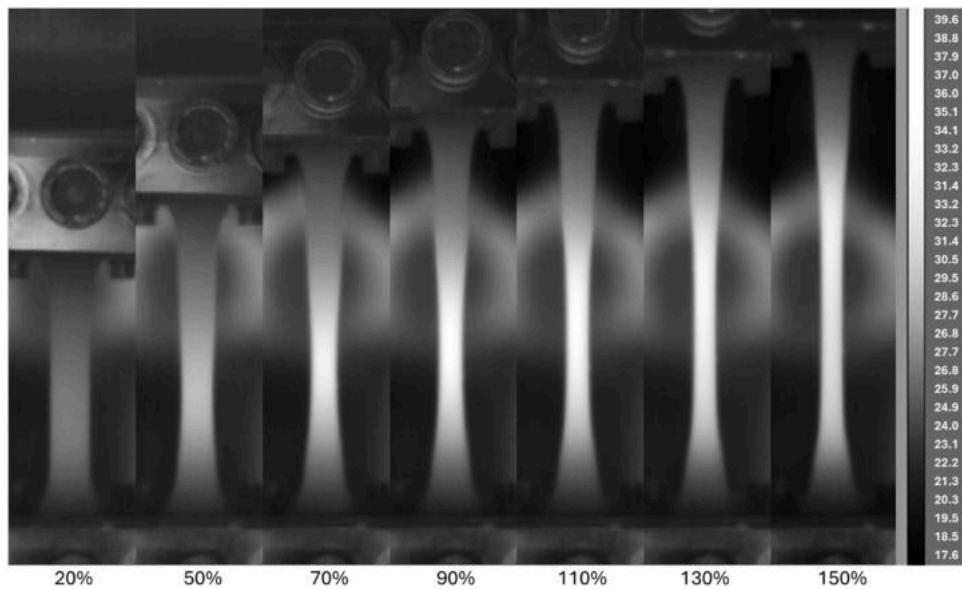


Fig. 15. IRT results of the RT10S_2 (recycled) specimen.

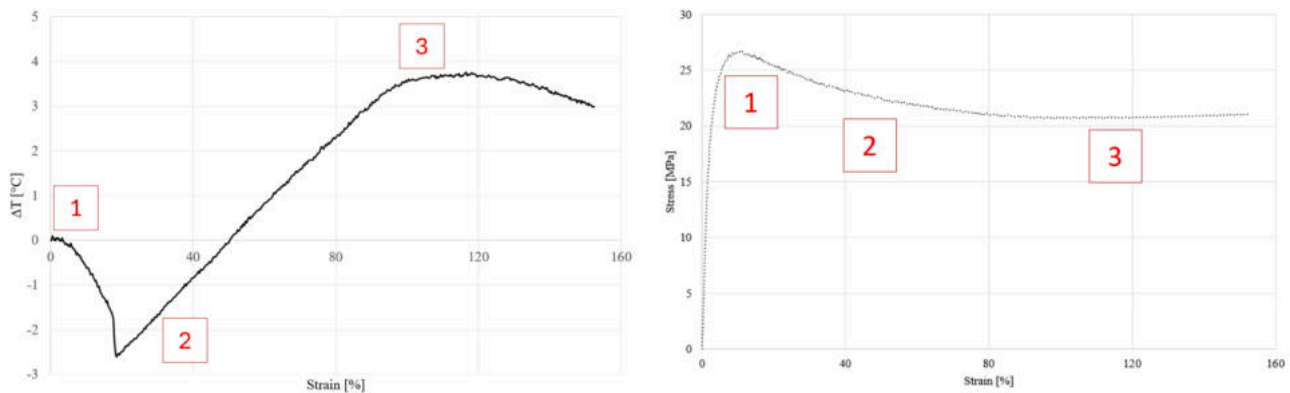


Fig. 16. IRT curve ΔT /Strain and curve Stress/Strain of the RT10S_2 (recycled) specimen.

temperature remains initially almost constant and then begins to decrease, the material still deforms in a homogeneous manner (zone 1 in the Fig. 14). Immediately after the maximum stress, the stress–strain curve begins to decrease and, over almost the same strain interval, the temperature also falls until it reaches negative values (zone 2 in the Fig. 14). This stage may be associated with thermoelastic effects and with phenomena of internal reorganisation within the polymer (Torres et al., 2016). Subsequently, the temperature increases, while the stress–strain curve enters a flatter, or nearly steady, region. In this zone, necking of the specimen occurs local energy dissipation increases and, consequently, the temperature rises significantly (zone 3 in the Fig. 14). In semicrystalline polymers, this phase is in fact characterised by chain orientation and microstructural transformations, so that a significant part of the plastic work is converted into heat (Song et al., 2023).

In Fig. 16, the evolution of the maximum temperature as a function of strain is compared with the stress–strain curve for specimen RT10S_2. Also in this case, in the initial stage, the stress increases up to its peak value, while the temperature remains initially almost constant and then begins to decrease (zone 1 in the Fig. 16). This behaviour may again be attributed to the thermoelastic effects of the material, which lead to an initial cooling. In the following stage, as the temperature continues to decrease, the material enters a phase of internal reorganization of the polymer chains (zone 2 in the Fig. 16). When the temperature starts to rise, the stress–strain curve approaches the flatter region, where the onset of necking occurs, and the temperature begins to increase

accordingly (Wattrisse et al., 2002). In the final region, while the stress–strain curve shows a stable plateau, the temperature reaches a maximum value and then tends to decrease (zone 3 in the Fig. 16). This may be due to the dissipative process becoming more stable and the heat generated being transferred to the rest of the specimen.

The failure mechanisms observed in the microscopic images for the welded specimens are supported by the DIC images shown in Fig. 17. In Fig. 17a, the failure of the VT10BWM_1 specimen occurs via interfacial failure due to the presence of defects, as also evidenced by the fracture surface shown in Fig. 11a. However, the specimen shows a pronounced necking region, starting from a strain of 40%, which propagates in the gauge length, exhibiting appreciable deformation due to fibril elongation typical of the machine welded samples. In Fig. 17b, specimen VT15BWM_2 shows low strain values concentrated in the welding zone, which rapidly propagate leading to failure. This fracture mechanism is corroborated by the fracture surface of the specimen, shown in Fig. 11b. In Fig. 17c, specimen VT15BWM_6 initially exhibits a deformation mechanism similar to that of the non-welded VT15S_2 specimens (Fig. 7b), with a pronounced necking region that propagates in the gauge length. Failure of the specimen occurs due to fibril elongation, as also evidenced by the fracture surface shown in Fig. 11d. A third fracture mechanism is observed and shown in Fig. 17d for specimen VT15BWE_4. In this case, a pronounced necking region initially forms, however the deformation does not propagate, and failure occurs rapidly in the weld region, as also evidenced by the fracture surface shown in Fig. 11e.

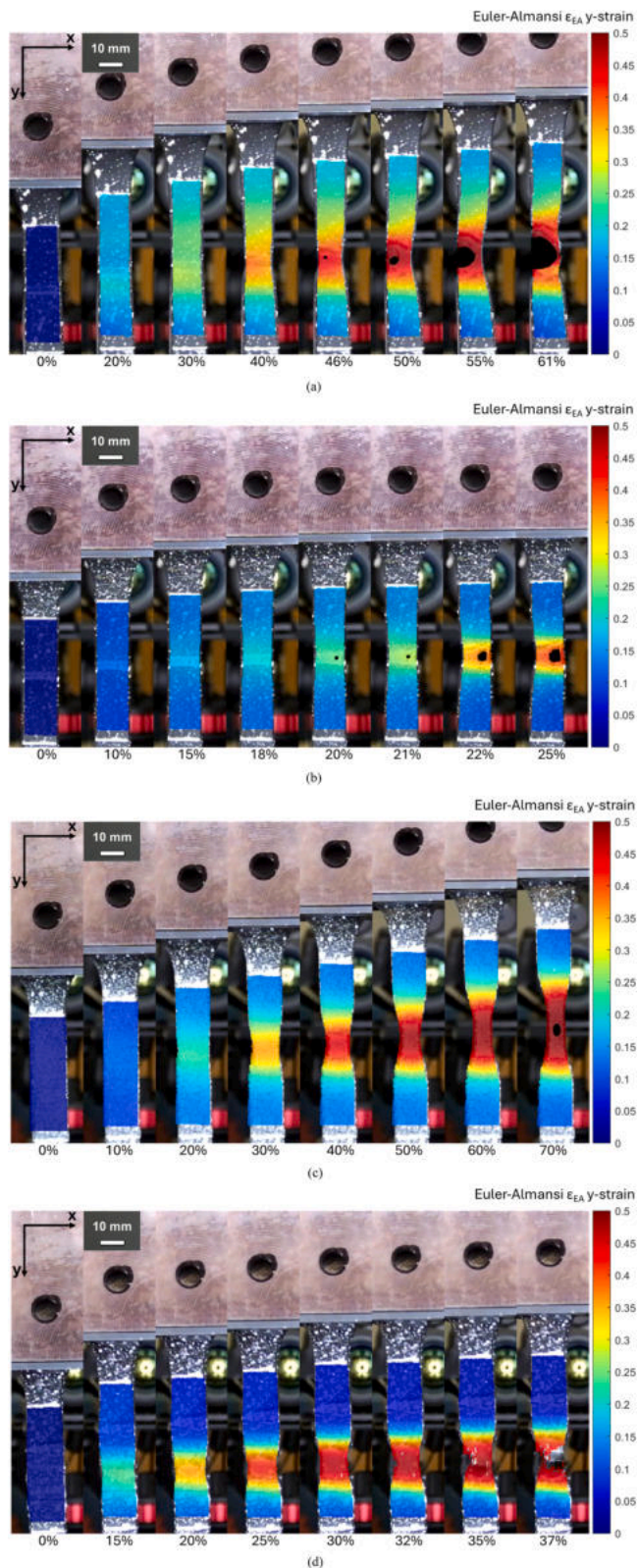


Fig. 17. DIC analysis results of HDPE welded specimens: (a) VT10BWM_1; (b) VT15BWM_2; (c) VT15BWM_6; (d) VT15BWE_4.

The plastic strain localisation is induced by intrinsic strain softening and triggered by local stress perturbation. An increase in the strain softening, thus an increased drop in the stress after the yield point, leads to a more localised plastic zone in the specimen's gauge length (van Breemen et al., 2012), as depicted in Figs 18a and 18b.

3.3. FT-IR and TGA results

The comparison between the FT-IR spectra of the v-HDPE and the r-HDPE, shown in Fig. 19, highlights a substantial overlap in the main spectral features, indicating that the fundamental chemical structure of the polymer is largely preserved during the recycling process. The characteristic bands of polyethylene, namely the C-H stretching vibrations in the 2850–2950 cm^{-1} region and the CH_2 deformation bands around 1470 and 720 cm^{-1} , are clearly observed in both specimens (Petrović et al., 2022). Their presence with nearly identical positions and shapes confirms that the saturated $-(\text{CH}_2)_n$ backbone remains intact and that no extensive chemical transformations occur, such as severe oxidative chain scission or crosslinking reactions.

Despite this overall similarity, some spectral details suggest microstructural modifications in the recycled material. In particular, several bands in the fingerprint region appear slightly broadened or show a reduction in intensity compared to the virgin material. These changes are commonly associated with a decrease in crystalline order and an increase in the amorphous fraction, typical effects observed in polymers subjected to repeated thermal and mechanical processing (Smidt and Schwanninger, 2005). During recycling, polyethylene chains may undergo partial fragmentation, a reduction in average chain length, or changes in entanglement density, all of which influence vibrational behaviour and thus the shape of IR bands.

Additional differences between the two samples may be attributed to trace oxidation or residual additives in the recycled material. Although no distinct bands associated with carbonyl (C=O) or hydroxyl (O-H) groups, key markers of polyethylene oxidation, are observed, slight baseline variations and subtle changes in the 1000–1200 cm^{-1} region may be compatible with the formation of very small amounts of oxidative products or interactions involving partially degraded chains (Chabira et al., 2012). It is worth noting that such features, when present only in traces, may be masked by the strong intensity of the dominant CH_2 vibrations.

Another relevant aspect concerns the definition of the band at approximately 720 cm^{-1} , typically attributed to the CH_2 rocking mode in crystalline regions. In the v-HDPE this band appears somewhat sharper, consistent with a more ordered microstructure. In the r-HDPE, however, this signal tends to be less pronounced, suggesting a reduction in the regular packing of polymer chains. This behaviour is well documented in the literature for polyethylene processed through multiple remelting cycles, in which subsequent crystallization is less efficient due to thermal history and topological rearrangements of the chains (Bhattarai et al., 2024).

A similar behaviour is observed when comparing the spectra of samples obtained through different welding techniques (VT15BWM_2 and VT15BWE_7), which show a substantial overlap of the main absorption bands, confirming that the welding process does not significantly alter the chemical composition of HDPE (Fig. 20). Minor differences in band intensity and sharpness can be observed, particularly in the CH_2 stretching and rocking regions, which may be attributed to variations in chain packing and local crystallinity induced by the different processing conditions (Sirbu et al., 2025).

However, a more detailed inspection of the fingerprint region (1800–1000 cm^{-1}) reveals a more complex behaviour. In this region, the extrusion-welded sample (VT15BWE_7) exhibits a noticeable attenuation and partial loss of definition of several absorption bands compared to the machine-welded sample (VT15BWM_2). This results in a smoother spectral profile, where distinct vibrational features appear less resolved.

This apparent reduction in spectral definition suggests that the extrusion process does not simply increase structural order but rather induces a redistribution of the supramolecular organization of the polymer. In particular, the combined effect of melt flow, shear forces, and rapid cooling may promote chain orientation and local densification while simultaneously reducing the regularity of crystalline domains or increasing the fraction of disordered regions. As a consequence,

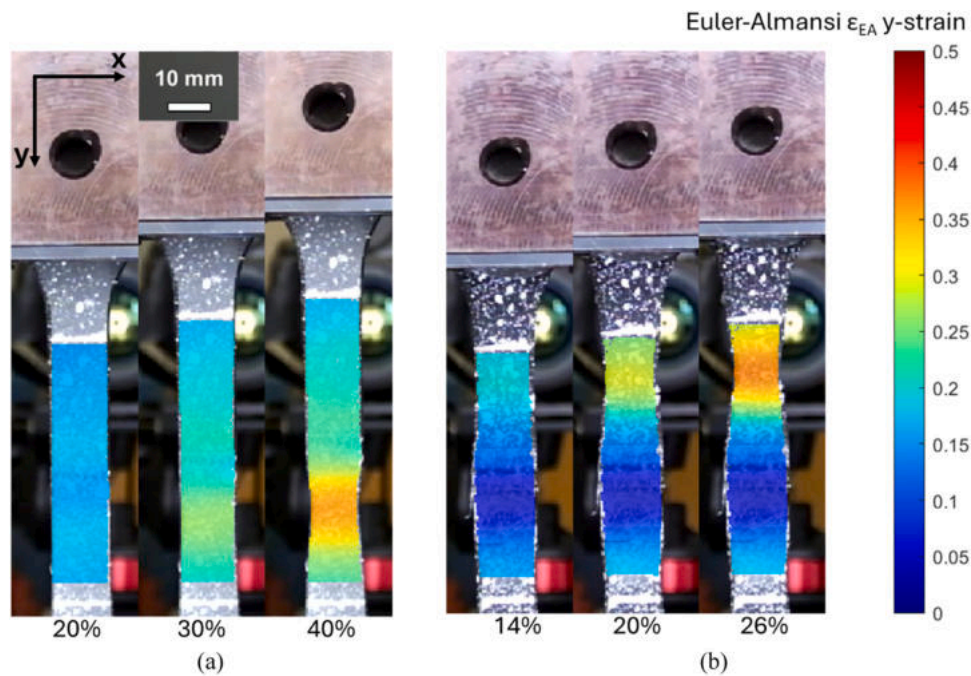


Fig. 18. DIC analysis results of HDPE welded specimens: (a) VT10BWM_6; (b) VT10BWE_5.

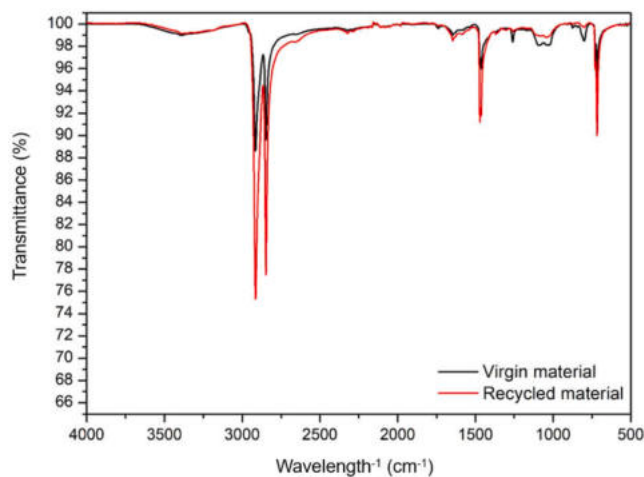


Fig. 19. FT-IR spectra of virgin and recycled HDPE.

vibrational modes that are highly sensitive to ordered packing become less pronounced in the FTIR spectrum.

Overall, the FT-IR analysis indicates that the recycling process and welding techniques do not significantly alter the primary chemical structure of polyethylene, which remains essentially comparable to that of the virgin material. Nevertheless, the differences observed in the shape and intensity of certain bands reflect modifications in the supra-molecular organization of the polymer. Although these changes do not compromise the molecular identity of the material, they may influence macroscopic properties such as stiffness (elastic modulus), mechanical strength, transparency, and thermal behaviour, properties that are often more sensitive to structural organization than to the chemical nature of the polymer chains themselves.

In summary, the FT-IR spectra show that the recycled material retains the fundamental features of polyethylene while bearing the signatures of thermomechanical stress undergone during reprocessing, including a slight loss of structural order and potential minor degradation or compositional heterogeneity. These observations are consistent with the expected behaviour of recycled polyolefin materials and

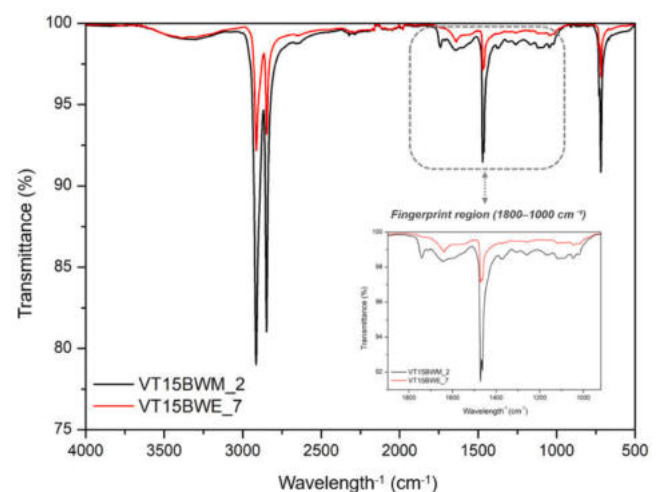


Fig. 20. FTIR spectra of welded HDPE samples (VT15BWM_2 and VT15BWE_7). The highlighted area corresponds to the fingerprint region (1800–1000 cm^{-1}), shown in detail in the inset to emphasize subtle differences in band shape and intensity associated with processing-induced microstructural variations.

provide useful support for assessing the overall quality of the processed polymer.

Between the two types of specimens, VT15S (virgin) and RT10S (recycled), the difference observed in the strain-softening region may be attributed to the microstructural modifications evidenced by FT-IR analysis. In particular, the reduction in band intensity observed in the recycled material is consistent with the mechanical behaviour reported in the stress-strain curves (Fig. 7b and c) and with the mechanical properties summarized in Table 4, confirming a decrease in structural organization after recycling.

The thermogravimetric analysis (TGA) of HDPE samples, obtained by butt fusion welding (VT15BWM_2) and extrusion welding (VT15BWE_7) (Fig. 21), shows a similar degradation behaviour, characterized by a single main weight loss step typical of polyolefin materials, occurring

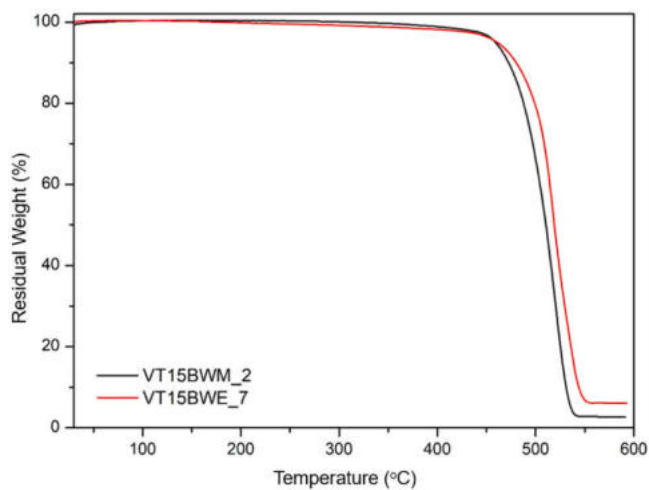


Fig. 21. TGA curves of HDPE samples obtained by butt fusion welding (VT15BWM_2) and extrusion welding (VT15BWE_7). The analysis was performed under argon flow.

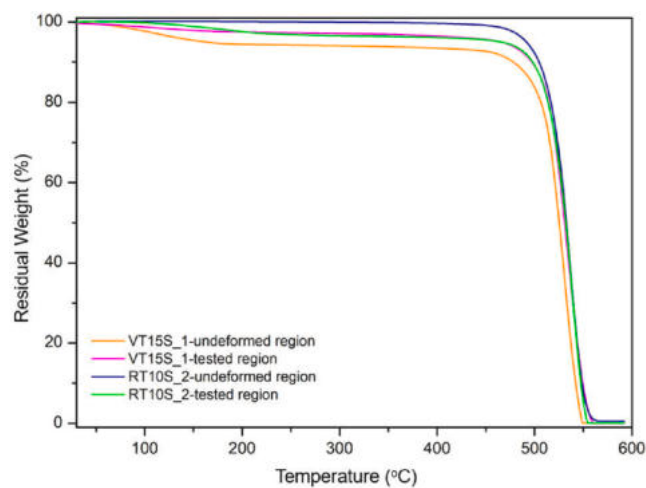


Fig. 22. TGA curves of HDPE samples comparing the tested region and the undeformed region for virgin (VT15S_1) and recycled (RT10S_2) materials. The analysis was performed under argon flow.

within the temperature range of approximately 450–570°C. This confirms that the fundamental decomposition mechanism of the polymer backbone remains unchanged regardless of the welding technique employed, in agreement with literature reports on HDPE systems (Dias et al., 2025). Despite this overall similarity, a clear difference in thermal stability between the two samples can be observed. In particular, the extrusion-welded sample (VT15BWE_7) remained stable up to 470°C and degraded up to 556°C, leaving a final residue of 5%, whereas the butt-fusion welded sample (VT15BWM_2) showed an earlier onset of degradation at 450°C, with decomposition ending at 543°C and a lower residue of 2%. Furthermore, the degradation process in the extrusion-welded sample extends to higher temperatures, confirming an overall shift of the degradation profile toward increased thermal resistance. This behaviour suggests that the extrusion process promotes a more homogeneous and compact microstructure, likely due to enhanced melt flow and shear conditions that facilitate chain rearrangement and improved packing.

Further insight into the thermal behaviour of HDPE was obtained by comparing different regions of the same specimens, distinguishing between the tested region and the undeformed region (Fig. 22). Both virgin (VT15S_1) and recycled (RT10S_2) materials exhibit a similar overall

degradation profile, characterized by a single main weight loss step within the typical temperature range of polyethylene decomposition. For the virgin HDPE sample (VT15S_1), a clear difference is observed between the tested region and the undeformed region. The tested region remained stable up to 490°C and degraded up to 562°C, whereas the undeformed region exhibited an initial mass loss of approximately 5% in the temperature range 100–200°C, followed by a second degradation stage starting at 476°C and ending at 548°C. The low-temperature mass loss can be attributed to the release of volatile or low-molecular-weight species rather than to degradation of the polymer backbone. The higher thermal stability observed in the tested region suggests that mechanical loading may induce local structural rearrangements, such as chain alignment and improved packing, resulting in a more thermally resistant microstructure. In contrast, the recycled HDPE sample (RT10S_2) exhibits a different trend. Although the onset of the main degradation step remains comparable to that of the virgin material, with values of 485°C for the tested region and 480°C for the undeformed region, the tested region also exhibits an initial mass loss of about 3% between 100 and 200°C. In addition, a lower final degradation temperature is observed for the tested region (560°C vs 570°C), together with a reduced residual mass (0.33% vs 0.7%). This behaviour indicates that mechanical loading does not produce a stabilizing thermal effect in recycled materials. Instead, the presence of pre-existing structural heterogeneities, such as chain scission, molecular weight reduction, and residual impurities introduced during recycling, limit the ability of the polymer to reorganize under stress and promotes the release of more labile fractions. A similar behaviour is widely reported in the literature, where recycled HDPE shows earlier degradation due to thermo-mechanical degradation and the presence of defects or impurities (Zhang et al., 2022). Additionally, recycled HDPE exhibits a slightly broader degradation profile compared to the virgin material, suggesting a higher compositional heterogeneity. This behaviour can be associated with a wider molecular weight distribution and the presence of fractions with different thermal stabilities, resulting from multiple processing cycles and the more complex nature of the recycled feedstock. A more pronounced difference concerns the residual mass at the end of the analysis. While virgin HDPE undergoes almost complete degradation, recycled samples exhibit measurable residues, which can be attributed to inorganic contaminants, fillers, pigments, or thermally stable additives accumulated during the material lifecycle. This observation is in agreement with previous studies reporting higher ash content and impurity levels in recycled materials, which directly contribute to the increased residue after thermal treatment (Petrović et al., 2022).

Overall, the TGA results indicate that, while the primary degradation mechanism of polyethylene remains unchanged, both the welding technique and the recycling process influence the microstructural organization of the material. These factors lead to variations in thermal stability, structural heterogeneity, and residual content. In particular, mechanical loading appears to enhance structural organization in virgin HDPE, whereas in recycled HDPE it interacts with pre-existing heterogeneities, leading to a more complex and less predictable thermal response. The effect of mechanical loading on thermal stability is therefore not intrinsic to HDPE itself, but strongly dependent on the prior structural history of the material.

4. Conclusions

This study provides an integrated experimental assessment of virgin and recycled HDPE materials and their welded joints for potential application in marine structural components. The combined results of tensile testing, DIC, IRT, and FT-IR analysis demonstrate that low-grade r-HDPE retains comparable yield stress and stiffness within the linear-elastic range, and that its essential chemical structure is preserved after recycling. The similarity of the measured mechanical properties to those of virgin HDPE is consistent with a low recycled content in the material blend, as inferred from the technical datasheet provided by the

supplier and in accordance with the threshold investigated by Tesfaw et al., 2022 for short-term mechanical performance. This suggests its potential feasibility, subject to long-term durability verification, as an environmentally responsible alternative for structural elements in boatbuilding governed by elastic design criteria.

The analysis of welded configurations highlights the robust short-term tensile performance, in terms of yield stress and stiffness, regardless of welding method, with all welded specimens maintaining yield stresses equivalent to those of the base materials. Notably, extrusion-welded joints exhibit higher joint stiffness (reflected in higher Young's modulus values of the welded regions) than both machine-welded joints and unwelded specimens, suggesting that the deposition-based welding technique may enhance joint rigidity when properly executed. Failure analyses reveal that fracture phenomena are largely confined to thicker welded specimens and are primarily linked to localized defects at the weld interface, confirming the critical role of weld quality control in HDPE shipbuilding applications.

FT-IR analyses support the mechanical findings by showing that the essential chemical structure of HDPE is preserved after recycling, with only minor reductions in crystallinity that do not significantly compromise mechanical integrity. The strain-field and thermal measurements obtained through DIC and IRT further validate the deformation mechanisms observed in the mechanical tests, including necking, localized strain accumulation, and post-yield propagation. Overall, the results confirm that both virgin and recycled HDPE, along with their welded joints, present a reliable short-term tensile response, in terms of yield stress and Young's modulus, suitable for marine applications governed by elastic design criteria.

These results are based on a quasi-static tensile testing campaign; further experimental testing is required for evaluating long-term material properties, including creep behaviour and viscoelastic response, as well as the sensitivity of recycled HDPE and welded joints to defects, process parameters, and organic or inorganic contamination.

From a research perspective, several aspects could be further explored to fully establish the structural applicability of HDPE. Future work should focus on fatigue, creep, and environmental durability, as well as the sensitivity of welded joints to defects and process parameters. Validation on structural-scale components and the integration of these findings into performance-based design approaches will be essential to support the broader adoption of recycled HDPE in marine applications.

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Writing – review & editing, Supervision, Resources, Methodology, Investigation, Data curation, Conceptualization. **Alberto Marinò:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Giuseppe Brando:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fabio Distefano:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Consuelo Celesti:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gabriella Epasto:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vincenzo Crupi:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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