

Strain rate-dependent constitutive modelling of stainless steels

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ABSTRACT

A strain rate-dependent constitutive model for stainless steels, calibrated against 184 coupon test results assembled from the literature on austenitic, ferritic, duplex and martensitic alloys, is presented. The rate-dependent material behaviour of two austenitic stainless steels, EN 1.4307 and EN 1.4678, was first examined experimentally. A total of 46 coupon tests were conducted, at different strain rates ranging from 0.00018 s^{-1} to 2000 s^{-1} . The effect of strain rate on the strength and ductility of the tested stainless steels was analysed. The test results indicated that both the yield strength and ultimate strength of the two stainless steels are strain rate-dependent, though each exhibited distinct trends. As the strain rate increased, the yield strength exhibited an increasing trend, whereas the ultimate strength initially decreased at strain rates below 0.1 s^{-1} and then increased at higher strain rates. Compared to the normal-strength EN 1.4307 stainless steel, the high-strength EN 1.4678 stainless steel exhibited lower sensitivity to strain rates, as reflected by lower dynamic increase factors. The Johnson–Cook model was calibrated to match the observed response of the studied grades. Based on both the newly obtained test results, as well as additional experimental data collected from previous studies, a continuous dynamic constitutive model applicable to all stainless steels — expressed as a function of strain rate and yield strength — was developed by combining a modified Cowper–Symonds formulation for the strain rate effect with the two-stage Ramberg–Osgood model for describing the stress-strain curve. The developed formulations are suitable for inclusion in advanced analytical models and numerical simulations of stainless steel elements under high strain rate loading scenarios.

1. Introduction

Stainless steel is widely used across a range of industries for its excellent mechanical performance and well-known durability [1,2]. Applications that exploit its ductility [3], energy absorption characteristics [4] and resistance to elevated temperatures [5,6] are also becoming increasingly common. Within the context of construction, several recent extreme events, failures and acts of terrorism have highlighted the vulnerabilities of infrastructure to impacts, explosions and earthquakes, underscoring the need for greater inherent resilience. The strategic adoption of stainless steel components, particularly within protective elements and critical regions of structures, such as connections, braces and fuses, offers an effective means of enhancing structural resilience under extreme loading conditions. Various stainless steel grades with excellent energy absorption and deformation capacity have been developed, making them particularly well-suited to applications in which strain rate effects can be significant. To enable accurate performance predictions and to facilitate wider use, a greater understanding

and an accurate description of the dynamic constitutive response of stainless steel is needed.

A number of experimental studies into the dynamic behaviour of mild steel [7,8], high strength steel [7,9] and stainless steel [10,11] have been conducted using different test apparatus, including universal testing machines for low strain rates ($10^{-5} - 10 \text{ s}^{-1}$) [12], high-speed tensile testing machines for low and medium strain rates ($10^{-2} - 10^2 \text{ s}^{-1}$) [11,13], split Hopkinson pressure or tensile bars (SHPB or SHTB) for high strain rates ($10^2 - 10^4 \text{ s}^{-1}$) [7,11] and drop-weight impact test systems for strain rates of $10^1 - 10^3 \text{ s}^{-1}$ [12]. Significant strain rate effects have been observed in austenitic stainless steels, with the increase in yield strength attributed to strain-induced martensitic transformation [11]. Several studies have also reported that the strain hardening behaviour of austenitic stainless steel is influenced by the rise in temperature due to adiabatic heating during high speed plastic deformation [11,13,14]. The combined effects of thermal softening and strain rate sensitivity have been extensively investigated and are incorporated into constitutive models, such as the well-known

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Table 1

Nominal chemical composition of the adopted stainless steels (% by weight).

Grade	Cr	Mn	Ni	C	N	Fe
EN 1.4307 (304 L)	18.1	–	8.1	0.02	–	Balance
EN 1.4678 (Forta H500)	14.0	16.0	–	0.32	0.32	Balance

Table 2

Nominal mechanical properties of the adopted austenitic stainless steels, as provided by the manufacturer [24].

Grade	E_a (GPa)	f_y (MPa)	f_u (MPa)	ε_f (%)
EN 1.4307 (304 L)	200	300	600	55
EN 1.4678 (Forta H500)	200	530	900	50

Johnson–Cook model, where the influence of adiabatic heating is typically accounted for implicitly through temperature-dependent material parameters [11]. Previous studies have also examined the dynamic mechanical behaviour of ferritic [15] and duplex [16] stainless steels, highlighting differences in strain rate sensitivity due to their distinct microstructures and alloy compositions. In particular, the manganese content has been shown to influence the activation of specific deformation mechanisms, such as slip and twinning [15].

Based on dynamic experimental data, several classical constitutive models to consider strain rate effects have been proposed, including the Cowper–Symonds (C–S) model [17], Johnson–Cook (J–C) model [18], Zerilli–Armstrong (Z–A) model [19], Khan–Huang–Liang (K–H–L) model [20] and a linear combination of the Hollomon and Voce (H/V) model [21]. These models have been modified through material grade-specific calibration [9,13], combined and adapted to incorporate thermal softening effects [10], in order to accurately characterise the dynamic stress-strain response of metallic materials for structural design and numerical analysis.

Although the strain-rate sensitivity of stainless steels has been recognised in previous studies, the available experimental data are sometimes inconsistent, and full stress-strain curves at different strain rates

remain relatively scarce, owing to variations in testing apparatus and procedures, together with the limited strain-rate ranges covered in earlier investigations. To address this gap, the dynamic response of two austenitic stainless steel grades (EN 1.4307 and EN 1.4678) is examined in the present study through a comprehensive series of tensile and compressive tests spanning low to high strain rates. The experimental results are used to calibrate and modify the commonly used constitutive models – the C–S model and J–C model, for the accurate representation of the examined stainless steels under dynamic loading scenarios. The present dataset also expands the pool of reliable full stress-strain curves available for modelling purposes. Then, following extensive data collection from the literature and analysis, a new generalised dynamic constitutive model is proposed for stainless steel by combining a modified C–S formulation with the static two-stage Ramberg–Osgood expression, incorporating the effects of strain rate and material yield strength.

2. Experimental programme

The experimental programme comprised quasi-static, intermediate and high strain rate tests on tensile and compressive coupons extracted from 8 mm-thick EN 1.4307 (304 L) and 6 mm-thick EN 1.4678 (Forta H500) stainless steel plates. Nine nominal strain rate levels (eight levels for the EN 1.4678 stainless steel) ranging from 0.00018 s^{-1} to 2000 s^{-1} , leading to 46 specimens in total, were examined. EN 1.4307 and EN 1.4678 stainless steels were selected as representative normal-strength and high-strength grades, enabling the evaluation of strain rate effects and the proposed model across a broad strength spectrum. The quasi-static and dynamic tensile tests were conducted in accordance with ISO 26203-2:2011 [22], and the dynamic compressive tests were performed following ISO 26203-1:2024 [23].

2.1. Material and test specimens

The two investigated stainless steel grades – EN 1.4307 and EN 1.4678 – were manufactured by the Outokumpu Stainless Steel Company. The nominal chemical composition and mechanical properties of

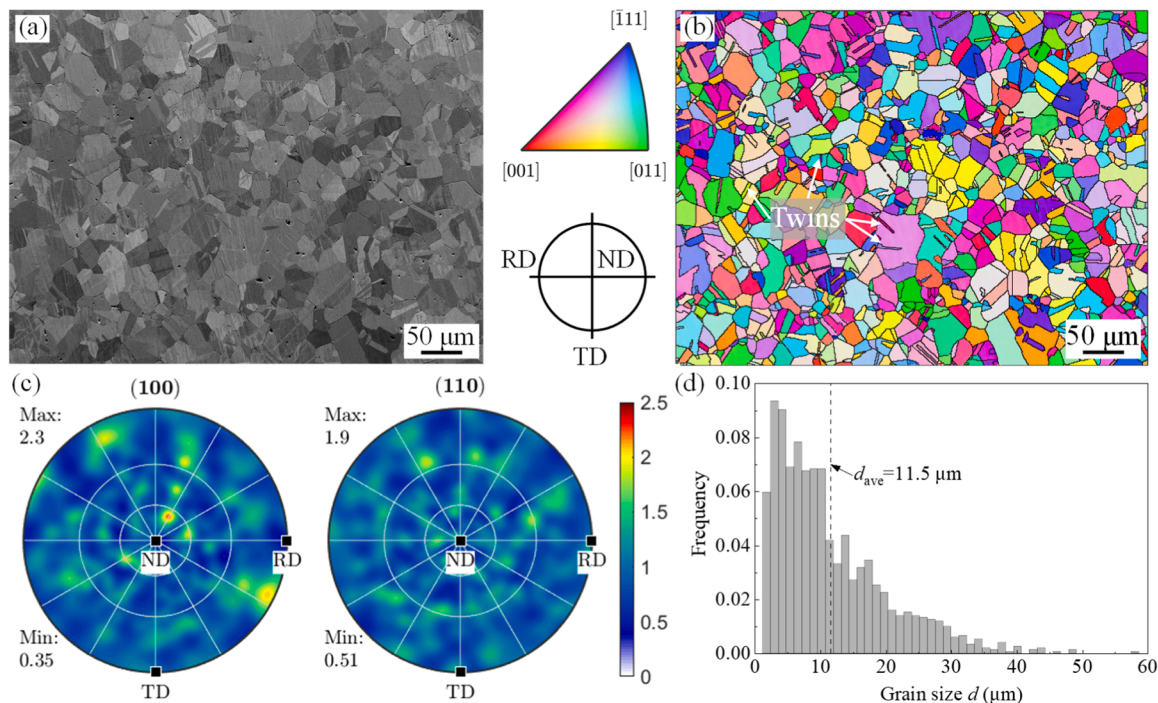


Fig. 1. Microstructural results for the examined EN 1.4678 stainless steel: (a) SEM micrograph, (b) IPF map, (c) pole figures and (d) grain size distribution.

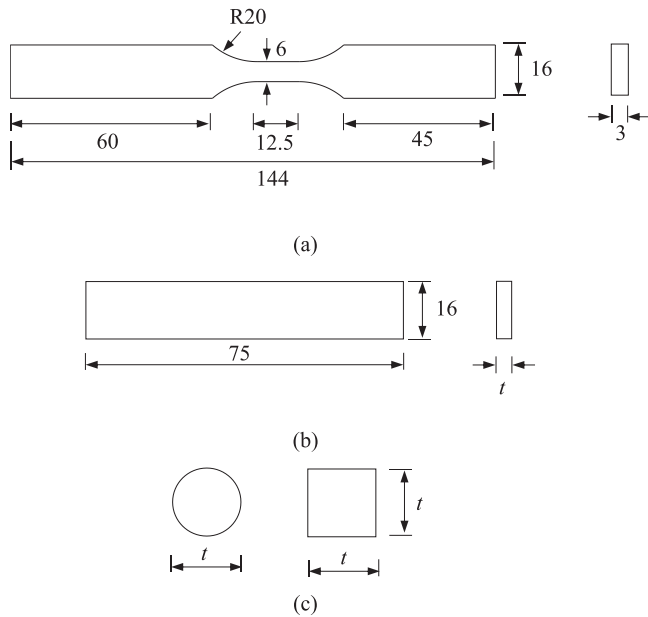


Fig. 2. Dimensions of the (a) tensile coupons for quasi-static and intermediate strain rate conditions, compressive coupons for (b) quasi-static and (c) high strain rate conditions (in mm).

the materials are provided in [Tables 1 and 2](#). The EN 1.4678 grade is a nickel-free austenitic stainless steel with a non-magnetisable microstructure and significant strain hardening characteristics due to twinning [24]. The microstructural features of this material are shown in [Fig. 1](#), which includes a scanning electron microscope (SEM) micrograph, an inverse pole figure (IPF) map, pole figures and a grain size distribution. The metallurgical sample preparation, SEM and electron backscatter diffraction (EBSD) were conducted in the Centre for Infrastructure Materials of the Department of Civil and Environmental Engineering at Imperial College London. The examined EN 1.4678 stainless steel exhibited an equiaxed grain structure with a noticeable number of twins, explaining its significant strain-hardening behaviour. The pole figures showed no preferred crystallographic orientation, which is typical of cold-worked austenitic stainless steel [25].

The dimensions of the quasi-static and dynamic tensile coupons were determined in accordance with ISO 26203-2 [22], and the dynamic compressive coupons were designed following ISO 26203-1 [23], as shown in [Fig. 2](#). A shorter parallel length was adopted for the dynamic tensile coupons compared to the standard dimensions specified for quasi-static tensile coupons in ISO 6892-1:2019 [26], to enable higher strain rates and to reduce data jitter during high-speed testing. To allow direct comparisons between the quasi-static and dynamic test results, particularly the elongations after fracture, the quasi-static test coupons were manufactured with the same dimensions as those used in the dynamic tensile tests. For the SHPB tests, cylinders were designed to have diameters and lengths equal to the plate thickness, i.e. 6 mm and 8 mm, respectively. The length-to-diameter ratio of these cylinders was set to 1.0 to reduce the inertial effect and to achieve dynamic stress equilibrium within a reasonable time. Quasi-static compressive coupons with a rectangular shape were used as benchmarks for the cylinders tested at high strain rates and to explore the potential tensile-compressive asymmetry. The coupon designation system starts with the material grade (EN 1.4701 or EN 1.4678), followed by the letters ‘T’ or ‘C’ to represent the tensile or compressive loading condition, the nominal strain rate (where the letter ‘QS’ denotes the quasi-static condition), and finally, a number to identify each individual coupon. For example, coupon EN 1.4678-T-100-2 is the second EN 1.4678 stainless steel tensile coupon tested at a nominal strain rate of 100 s^{-1} .

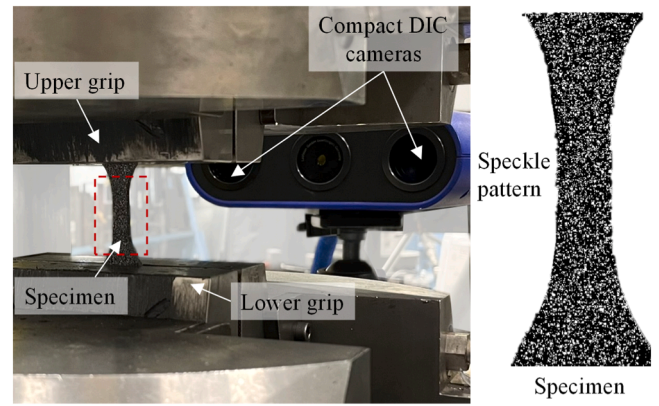


Fig. 3. Setup for quasi-static tensile coupon tests.

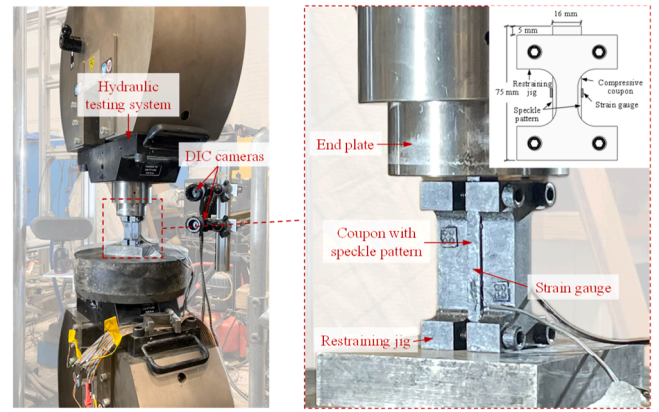


Fig. 4. Setup for quasi-static compressive coupon tests.

2.2. Quasi-static strain rate tests

For the tensile tests performed under quasi-static conditions, an Instron 8802 250 kN hydraulic testing machine was operated under displacement control in accordance with ISO 6892-1 [26]; the crosshead separation rates were set to achieve a strain rate of 0.007 s^{-1} prior to yielding and of 0.025 s^{-1} after yielding, with a smooth transition between the two rates. The test setup is shown in [Fig. 3](#). A four-camera StrainMaster Compact digital image correlation (DIC) system and an integrated LED illumination source were adopted to capture the strain and displacement fields along the parallel length on both faces of the coupons. Both faces of the coupons were prepared for DIC image acquisition by first spraying them with matte black paint along the parallel length to minimise reflection during image capture, followed by the application of a random pattern of white speckles to enable tracking of their relative movement between sequential images.

For the quasi-static compressive coupon tests, an Instron 600 kN hydraulic testing machine was employed, as shown in [Fig. 4](#). Prior to testing, both ends of each coupon were machined flat and square to ensure uniform compressive loading during the tests. A random white speckle pattern on a matte black background was applied on both sides of each coupon and captured using a four-camera StrainMaster Portable DIC system, combined with LED lights. A pair of electrical resistance strain gauges was affixed to opposite sides of the coupons at mid-height to record the longitudinal strains. The coupons were positioned in a restraining jig with the locking bolts fastened finger tight to avoid premature minor-axis buckling, while allowing expansion due to the Poisson's effect. The jig had a height of 70 mm, allowing the $75 \text{ mm} \times 16 \text{ mm}$ coupons to protrude sufficiently beyond the jig ends, to enable the application of compressive strains of up to approximately 6 %. A thin

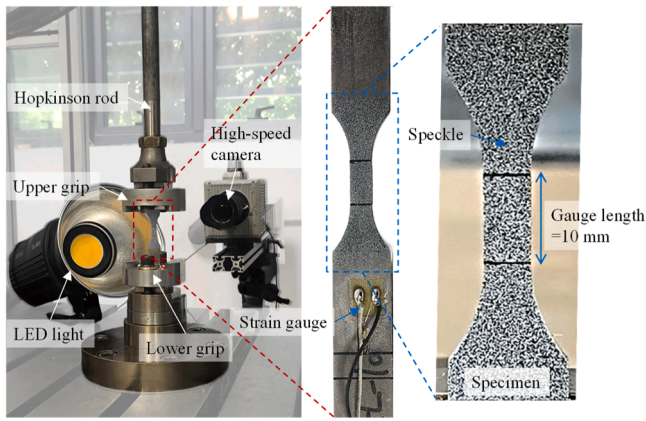


Fig. 5. Setup of intermediate strain rate tests.

layer of lubricating grease was applied to the coupon faces in contact with the jig to minimise frictional effects. A similar setup has been successfully used in previous studies [27–29]. The compressive tests were conducted under displacement control at a constant rate of 0.075 mm/min up to 3 % compressive strain. The applied load, which was measured by a load cell within the Instron testing machine, the crosshead movement and the strain gauge readings were recorded using the DATASCAN acquisition system. The transmitted load and DIC images in both the quasi-static tensile and compressive tests were captured using the DaVis 10 software package [30], with all data recorded at 1-second intervals.

2.3. Intermediate strain rate tests

The intermediate strain rate tests were conducted using a Zwick/Roell HTM5020 servo-hydraulic tensile testing machine with a maximum loading capacity of 50 kN and a loading rate up to 20 m/s. Tensile tests were performed using the setup shown in Fig. 5 at four nominal intermediate strain rates of 1 s^{-1} , 10 s^{-1} , 50 s^{-1} and 100 s^{-1} . A digital image correlation (DIC) system, equipped with a high-speed camera (Photron FASTCAM SA-X2 1000k) capable of capturing up to 675000 frames per second, was utilised to track the speckle movement and thus measure surface strains over the parallel length of each coupon

during tensile loading. For the higher strain rate tests (i.e. when $\dot{\epsilon} > 50 \text{ s}^{-1}$), the load cell readings were distorted by signal oscillations. To overcome this, two strain gauges were affixed to opposite faces of the longer gripped ends of the coupons (see Fig. 5) that experienced purely elastic deformations, were used to compute the applied load, as recommended by ISO 26203-2 [22]. The DIC images and strain gauge readings were recorded at high frequencies of 4000 Hz, 30000 Hz, 60000 Hz and 125000 Hz for the nominal strain rates of 1 s^{-1} , 10 s^{-1} , 50 s^{-1} and 100 s^{-1} , respectively.

2.4. High strain rate tests

The high strain rate tests were conducted using a SHPB system. Prior to testing, both ends of the test cylinders were machined flat and square to facilitate the introduction of axial load. The SHPB testing system, shown in Fig. 6, consisting of a strike bar, an incident bar, a transmission bar and an absorption bar, with the test specimen sandwiched between the perfectly aligned incident and transmission bars, was employed. The test procedure is as follows: the strike bar is first accelerated by a gas gun and impacts the front end of the incident bar with a diameter of 16 mm, which is made from high-strength stainless steel with a yield strength exceeding 1200 MPa, generating an elastic incident wave ϵ_I . Part of the incident wave passes through the cylinder specimen into the transmission bar, referred to as the transmitted wave ϵ_T , while the remainder is reflected back, referred to as the reflected wave ϵ_R . The waves are recorded by strain gauges with a high-speed digital storage oscilloscope. A laser velocimeter is used at the front end of the incident bar to measure the striking velocity. Tungsten carbide inserts with a diameter of 16 mm and a thickness of 4 mm, were positioned at the bar-specimen interfaces to prevent potential damage of the bar ends under high compressive stresses. All contact faces were lubricated with grease to minimise friction during testing. More details about the employed SHPB testing system can be found in previous studies [31,32].

3. Experimental results and discussion

3.1. Data processing method

The accurate quantification of the dynamic stress-strain response of the examined materials necessitates the determination of the actual strain rate under high-speed loading. Typical engineering and true

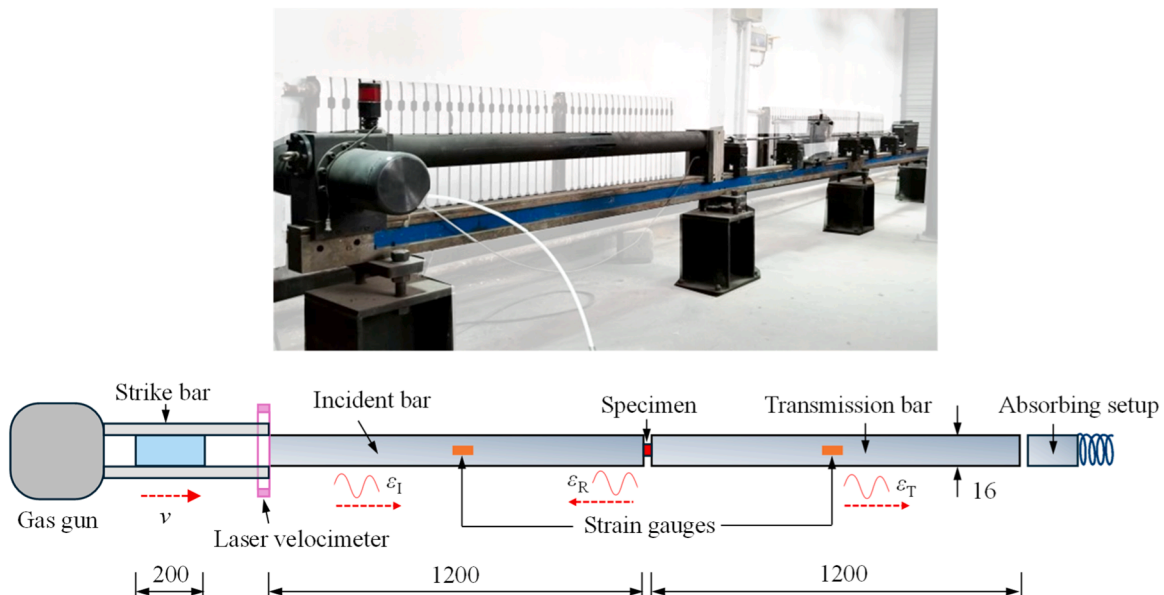


Fig. 6. Apparatus for high strain rate coupon tests (dimensions in mm).

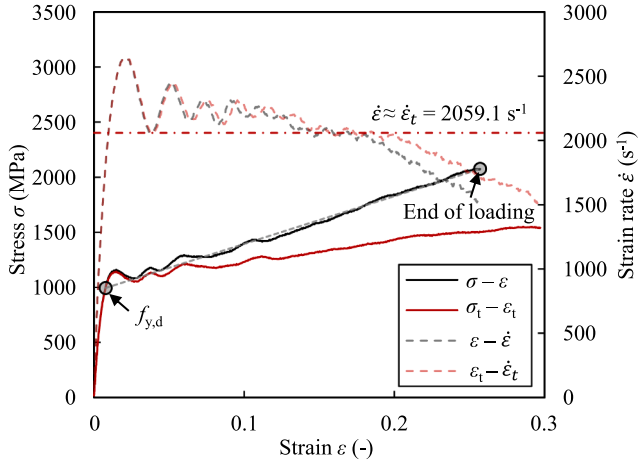


Fig. 7. Determination of the characteristic strain rates for a typical compressive coupon – EN 1.4678-C-2000-1.

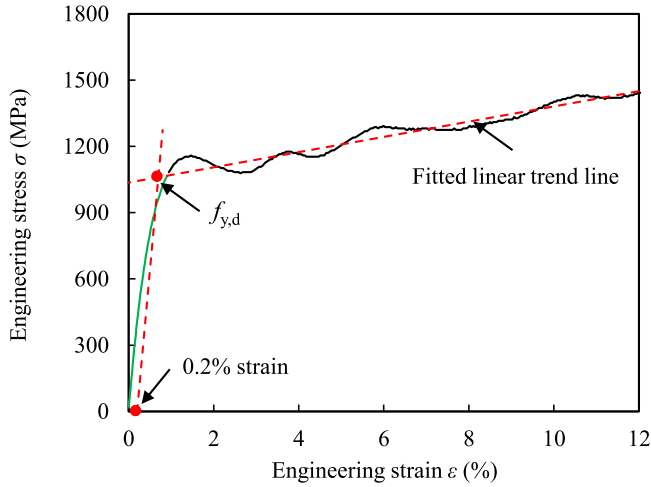


Fig. 8. Determination of dynamic yield strength for strain rates above 50 s⁻¹.

stress-strain curves and corresponding strain rates are presented in Fig. 7, showing the definition of the characteristic strain rate. The characteristic strain rate $\dot{\epsilon}$ is calculated as the average strain rate over the steady plastic deformation period, taken as the range between the

yield strength $f_{y,d}$ and the ultimate strength $f_{u,d}$ for the tensile tests and the end of loading phase for the compressive tests, in accordance with ISO 26203-2 [22].

Stainless steel normally exhibits no obvious yield plateau, and the yield strength at quasi-static and low strain rates is typically taken as the 0.2 % proof stress. The elastic portion of stress-strain curves from dynamic tests is often considered unreliable due to limited temporal resolution and measurement noise [10]. Additionally, the fluctuations in the dynamic stress-strain curves are more pronounced with increasing strain rates due to the inertia effect, particularly for strain rates beyond 50 s⁻¹. Therefore, the stress corresponding to the 0.2 % plastic strain is not suitable for the determination of the dynamic yield strength. For tests at strain rates above 50 s⁻¹, the intersection between the 0.2 % offset line and a trend line fitted to the steady strain-hardening segment [10,33], as shown in Fig. 8, is taken as the nominal dynamic yield strength $f_{y,d}$. The ultimate strength, the ultimate strain and the fracture strain for quasi-static and dynamic tensile tests are defined as the maximum stress value and corresponding strain in the engineering stress-strain curve and the percentage elongation after fracture, respectively.

The dynamic increase factor (DIF), which is defined as the ratio of the material property under dynamic loading to that under quasi-static loading, is widely used to quantify the strain rate effect on the mechanical properties of metallic materials. The three commonly used strength indices – DIF_y, DIF_u and DIF_{avg}, are described in Fig. 9. The dynamic increase factors for the yield strength f_y and the ultimate tensile strength f_u , i.e. DIF_y and DIF_u, can be calculated using

$$\text{DIF}_y = \frac{f_{y,d}}{f_y} \quad (1)$$

and

$$\text{DIF}_u = \frac{f_{u,d}}{f_u} \quad (2)$$

where $f_{y,d}$ and $f_{u,d}$ are the dynamic yield strength and ultimate strength, respectively, and f_y and f_u are the yield and ultimate strengths under quasi-static conditions. The average dynamic increase factor DIF_{avg} is defined over the full dynamic true stress-plastic strain curve [7,9] and calculated by averaging the DIF_i values from the yield point to the ultimate strength (or the end of loading) at defined true plastic strain intervals (see Eq.(3), where ϵ_y is the yield strain), with each DIF_i value equal to the ratio of the dynamic stress $\sigma_{i,d}$ to the corresponding quasi-static stress σ_i .

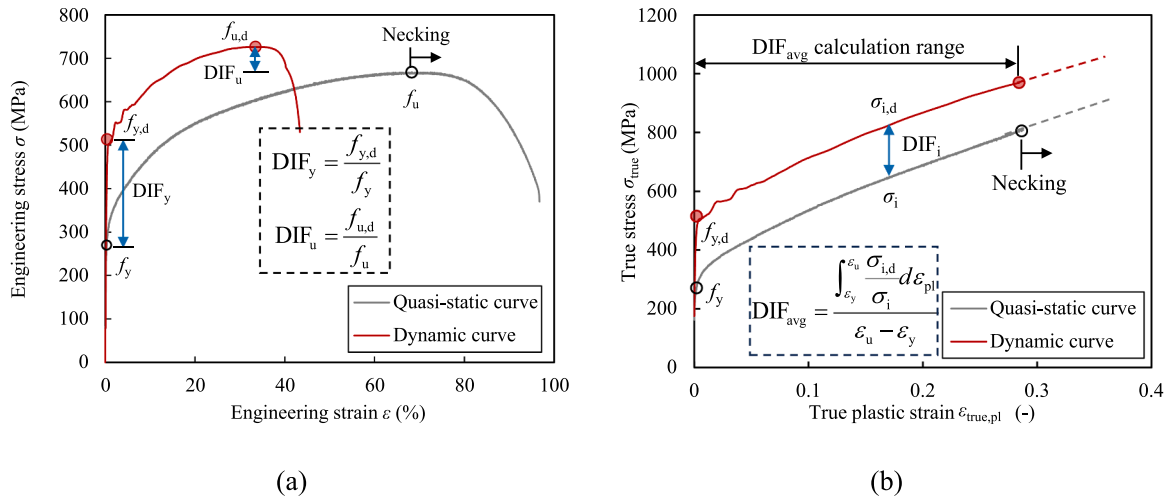


Fig. 9. Definition of dynamic increase factors: (a) DIF_y and DIF_u and (b) DIF_{avg}.

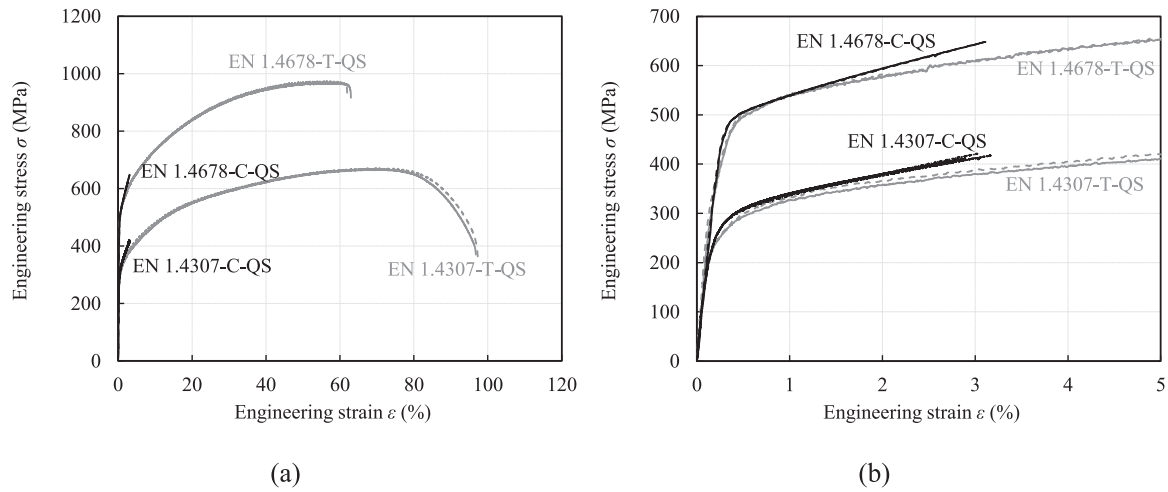


Fig. 10. Stress-strain curves obtained from quasi-static tensile and compressive tests: (a) full range and (b) initial range.

Table 3

Measured mechanical properties of examined stainless steels from quasi-static coupon tests.

Coupon ID	$\dot{\epsilon}$ (s^{-1})	E (GPa)	f_y (MPa)	$f_{p1.0}$ (MPa)	f_u (MPa)	ϵ_u (%)	ϵ_f (%)	n	$m_{1.0}$	m_u
EN 1.4307-T-QS-1	0.00018	205.1	269.7	330.4	667.9	68.3	96.7	6.1	2.5	3.1
EN 1.4307-T-QS-2	0.00018	206.0	273.1	342.5	671.1	70.8	97.2	6.2	2.7	3.3
EN 1.4307-C-QS-1	0.00081	208.8	290.1	347.4	—	—	—	5.1	1.7	—
EN 1.4307-C-QS-2	0.00080	205.3	289.3	345.0	—	—	—	5.1	1.7	—
EN 1.4307-C-QS-3	0.00082	213.2	287.8	343.6	—	—	—	5.4	1.5	—
EN 1.4678-T-QS-1	0.00018	214.5	483.5	550.1	969.9	55.9	63.0	5.6	2.1	2.8
EN 1.4678-T-QS-2	0.00018	228.3	487.3	551.9	974.8	53.2	62.1	6.5	2.1	2.6
EN 1.4678-C-QS-1	0.00081	200.0	500.5	555.9	—	—	—	7.2	1.5	—
EN 1.4678-C-QS-2	0.00079	206.3	498.8	554.3	—	—	—	8.0	1.5	—

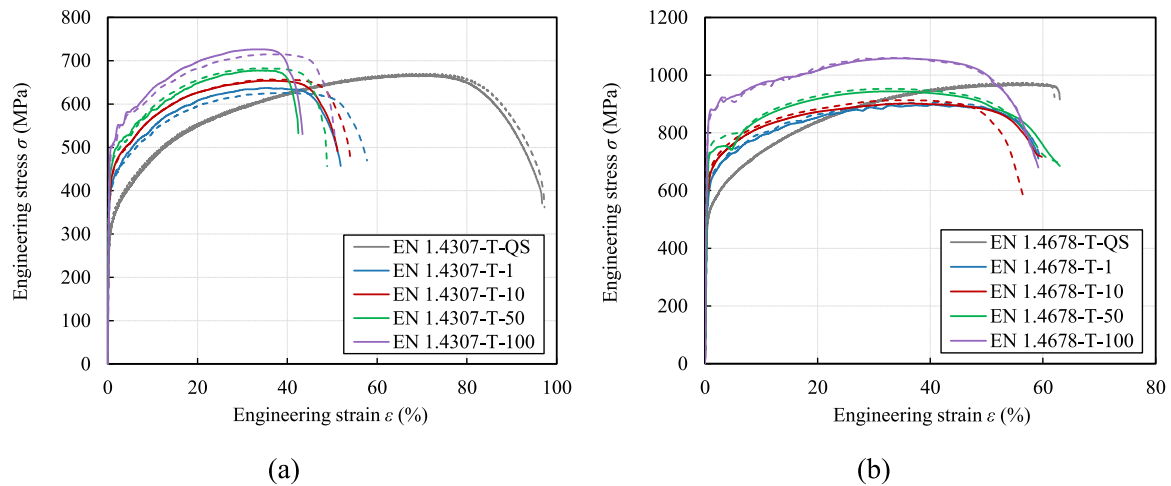


Fig. 11. Engineering stress-strain curves obtained from intermediate tensile coupon tests on: (a) EN 1.4307 and (b) EN 1.4678 stainless steel.

$$DIF_{avg} = \frac{\int_{\epsilon_y}^{\epsilon_u} \frac{\sigma_{id}}{\sigma_i} d\epsilon_{pl}}{\epsilon_u - \epsilon_y} \quad (3)$$

3.2. Quasi-static strain rate tests

Fig. 10 shows the engineering tensile and compressive stress-strain curves for the two stainless steel grades under quasi-static conditions. The pairs (tension and compression) of test coupons showed nearly identical stress-strain responses, both with no distinct yield point or yield plateau, as is customary for stainless steel [34,35]. The 0.2 % proof

strength was taken as the nominal yield strength f_y , following the recommendations of ISO 6892-1 [26]. The key mechanical properties, including the measured strain rate $\dot{\epsilon}$, the Young's modulus E , the yield strength f_y , the 1.0 % proof strength $f_{p1.0}$, the ultimate tensile strength f_u and the corresponding strain ϵ_u , the elongation after fracture ϵ_f and the coefficients (n , $m_{1.0}$ and m_u) of the two-stage Ramberg–Osgood model [36–38], are summarised in Table 3. Compared to the tensile coupons, the compressive coupons exhibited 3 %–6 % higher yield strengths, which is consistent with previous findings [28]; overall, the observed tension-compressive asymmetry of the tested stainless steels under

Table 4

Summary of measured mechanical properties of EN 1.4307 (304 L) stainless steel coupons at different strain rates.

Coupon ID	$\dot{\epsilon}$ (s ⁻¹)	E (GPa)	f_y (MPa)	f_u (MPa)	ϵ_u (%)	ϵ_f (%)	DIF _y	DIF _u	DIF _{avg}	DIF _{eu}	DIF _{ef}
EN 1.4307-T-QS-1	0.00018	205.1	269.7	667.9	68.3	96.7	0.99	1.00	1.01	0.98	1.00
EN 1.4307-T-QS-2	0.00018	206.0	273.1	671.1	70.8	97.2	1.01	1.00	0.99	1.02	1.00
EN 1.4307-T-1-1	0.91	218.9	368.7	637.2	35.5	51.9	1.36	0.95	1.13	0.51	0.54
EN 1.4307-T-1-2	0.99	215.6	362.2	625.7	38.2	53.0	1.33	0.93	1.10	0.55	0.55
EN 1.4307-T-10-1	10.4	204.3	382.1	653.8	35.8	47.0	1.41	0.98	1.17	0.51	0.48
EN 1.4307-T-10-2	10.2	195.8	381.3	656.5	36.0	46.0	1.40	0.98	1.17	0.52	0.47
EN 1.4307-T-50-1	43.5	195.4	423.0	677.7	34.5	42.4	1.56	1.01	1.22	0.50	0.44
EN 1.4307-T-50-2	46.8	222.9	431.3	682.6	34.6	46.0	1.59	1.02	1.23	0.50	0.47
EN 1.4307-T-100-1	110.3	199.9	462.7	726.1	33.5	42.0	1.70	1.08	1.32	0.48	0.43
EN 1.4307-T-100-2	122.2	178.0	417.1	714.9	38.5	44.0	1.54	1.07	1.28	0.55	0.45
EN 1.4307-C-QS-1	0.00081	208.8	290.1	–	–	–	1.00	–	1.02	–	–
EN 1.4307-C-QS-2	0.00080	205.3	289.3	–	–	–	1.00	–	1.02	–	–
EN 1.4307-C-QS-3	0.00082	213.2	287.8	–	–	–	1.00	–	1.02	–	–
EN 1.4307-C-500-1	421.5	202.9	477.4	–	–	–	1.65	–	1.44	–	–
EN 1.4307-C-500-2	403.2	202.4	468.2	–	–	–	1.62	–	1.43	–	–
EN 1.4307-C-1000-1	862.7	209.6	523.2	–	–	–	1.81	–	1.50	–	–
EN 1.4307-C-1000-2	885.2	191.6	518.7	–	–	–	1.79	–	1.48	–	–
EN 1.4307-C-1000-3	837.7	218.1	532.3	–	–	–	1.84	–	1.52	–	–
EN 1.4307-C-1200-1	1181.7	214.8	546.9	–	–	–	1.89	–	1.52	–	–
EN 1.4307-C-1200-2	1178.7	220.6	546.5	–	–	–	1.89	–	1.53	–	–
EN 1.4307-C-1500-1	1460.1	207.1	551.1	–	–	–	1.91	–	1.52	–	–
EN 1.4307-C-1500-2	1482.2	220.5	554.9	–	–	–	1.92	–	1.52	–	–
EN 1.4307-C-1500-3	1439.4	234.5	551.3	–	–	–	1.91	–	1.53	–	–

Table 5

Summary of measured mechanical properties of EN 1.4678 (H500) stainless steel coupons at different strain rates.

Coupon ID	$\dot{\epsilon}$ (s ⁻¹)	E (GPa)	f_y (MPa)	f_u (MPa)	ϵ_u (%)	ϵ_f (%)	DIF _y	DIF _u	DIF _{avg}	DIF _{eu}	DIF _{ef}
EN 1.4678-T-QS-1	0.00018	214.5	483.5	969.9	55.9	63.0	1.00	1.00	1.00	1.02	1.01
EN 1.4678-T-QS-2	0.00018	228.3	487.3	974.8	53.2	62.1	1.00	1.00	1.00	0.98	0.99
EN 1.4678-T-1-1	0.81	198.6	550.9	898.1	40.6	56.0	1.13	0.92	1.04	0.74	0.90
EN 1.4678-T-1-2	1.06	208.8	566.5	905.9	41.1	43.3	1.17	0.93	1.05	0.75	0.69
EN 1.4678-T-10-1	7.5	233.9	588.0	901.9	35.7	59.8	1.21	0.93	1.07	0.65	0.96
EN 1.4678-T-10-2	10.0	210.9	629.4	913.5	35.6	56.6	1.30	0.94	1.09	0.65	0.91
EN 1.4678-T-50-1	67.4	192.1	696.5	944.0	32.7	58.0	1.43	0.97	1.13	0.60	0.93
EN 1.4678-T-50-2	61.5	172.4	694.5	952.9	32.3	61.0	1.43	0.98	1.16	0.59	0.98
EN 1.4678-T-100-1	83.8	239.5	828.4	1058.3	33.9	56.0	1.71	1.09	1.29	0.62	0.90
EN 1.4678-T-100-2	81.1	229.9	802.5	1060.4	32.7	58.0	1.65	1.09	1.29	0.60	0.93
EN 1.4678-C-QS-1	0.00081	200.0	500.5	–	–	–	1.00	–	0.99	–	–
EN 1.4678-C-QS-2	0.00079	206.3	498.8	–	–	–	1.00	–	0.99	–	–
EN 1.4678-C-500-1	485.6	218.8	876.7	–	–	–	1.75	–	1.52	–	–
EN 1.4678-C-500-2	512.0	208.7	883.7	–	–	–	1.77	–	1.53	–	–
EN 1.4678-C-1000-1	1233.1	217.7	955.4	–	–	–	1.91	–	1.49	–	–
EN 1.4678-C-1000-2	1181.4	230.3	957.9	–	–	–	1.92	–	1.51	–	–
EN 1.4678-C-1000-3	1152.5	245.5	968.5	–	–	–	1.94	–	1.53	–	–
EN 1.4678-C-1500-1	1644.8	215.9	986.6	–	–	–	1.97	–	1.50	–	–
EN 1.4678-C-1500-2	1691.2	235.4	982.3	–	–	–	1.97	–	1.47	–	–
EN 1.4678-C-1500-3	1693.8	201.2	974.7	–	–	–	1.95	–	1.48	–	–
EN 1.4678-C-2000-1	2059.1	212.3	993.9	–	–	–	1.99	–	1.48	–	–
EN 1.4678-C-2000-2	2063.3	231.9	1007.1	–	–	–	2.02	–	1.47	–	–
EN 1.4678-C-2000-3	2070.6	198.4	1002.4	–	–	–	2.01	–	1.47	–	–

quasi-static conditions was not pronounced.

3.3. Intermediate strain rate tests

The engineering stress-strain curves of the two examined stainless steel grades at intermediate strain rates are presented in Fig. 11. The dynamic stress-strain curves are generally higher than the quasi-static stress-strain curve due to the strain rate effect. However, when the engineering strain exceeds 0.3, the quasi-static stress-strain curves for both grades intersect and even exceed those curves at strain rates of 1 s⁻¹ to 50 s⁻¹. This behaviour can be attributed to the material softening effect of stainless steels induced by adiabatic heating during plastic deformation. A quantitative evaluation of combined strain rate and temperature effect on the mechanical properties, particularly on the ultimate strength, is described in Section 3.6. Similar observations have been reported in previous studies for the dynamic response of EN 1.4301 (304) [11,39,40], EN 1.4307 (304 L) [41] and EN 1.4404 (316 L) [42]

austenitic stainless steel.

The key measured mechanical properties are summarised in Table 4 for the EN 1.4307 (304 L) stainless steel and

Table 5 for the EN 1.4678 (Forta H500) stainless steel, respectively, where $\dot{\epsilon}$ is the measured strain rate, f_y is the yield (i.e. 0.2 % proof) strength, f_u is the ultimate tensile strength, ϵ_u is the strain at the ultimate tensile strength, ϵ_f is the fracture strain, and DIF_y, DIF_u and DIF_{avg} are the dynamic increase factors for the yield strength, ultimate tensile strength and full plastic flow curve, respectively. The material properties of the examined stainless steels at the quasi-static and high strain rates, are also provided in Tables 4 and 5.

3.4. High strain rate tests

The output signals from the strain gauges on the incident and transmission bars from the high strain rate tests are shown in Fig. 12. According to the basic principle of the SHPB testing system, the

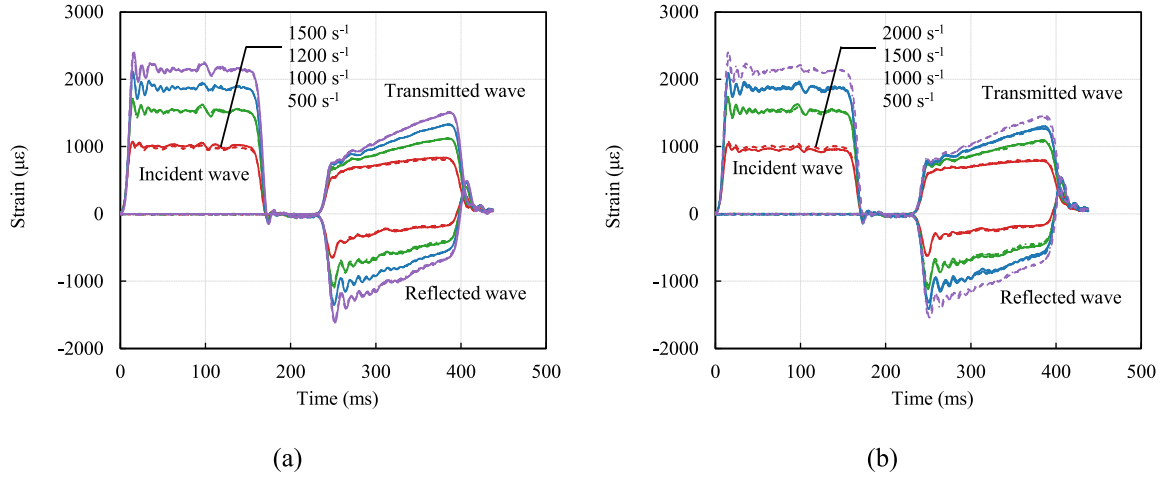


Fig. 12. Typical strain waves obtained from SHPB tests on: (a) EN 1.4307 and (b) EN 1.4678 stainless steel.

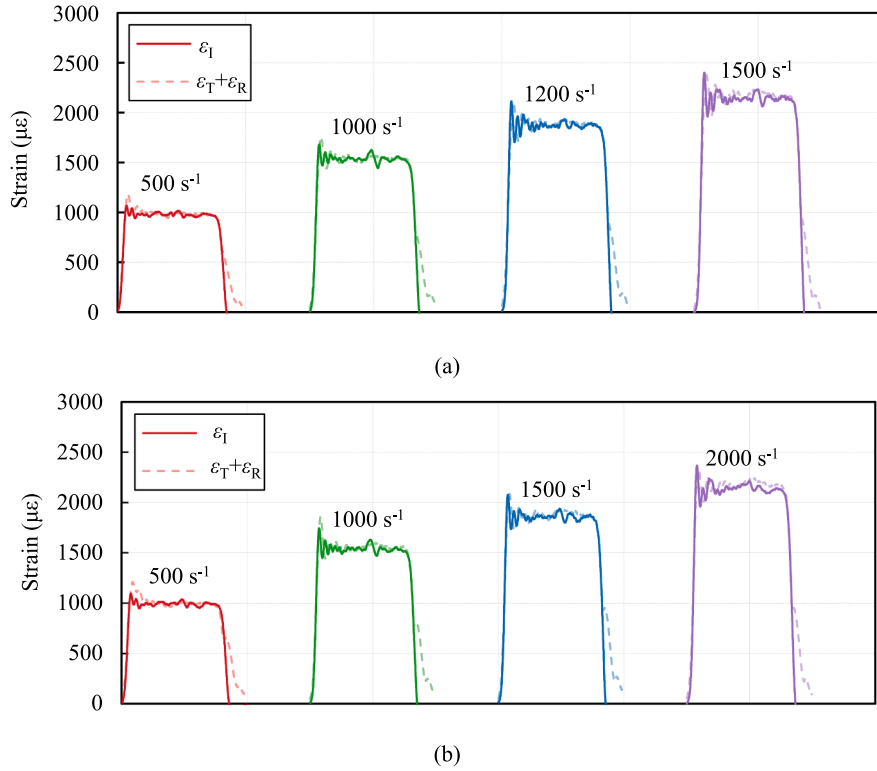


Fig. 13. Validation of the strain wave data from SHPB tests: (a) EN 1.4307 and (b) EN 1.4678 stainless steel.

superposition of the transmitted strain wave ε_T and the reflected strain wave ε_R should be equal to the incident strain wave ε_I , i.e. $\varepsilon_I = \varepsilon_R + \varepsilon_T$. Typical strain wave signals are shown in Fig. 13, confirming the adherence to this principle and hence the reliability of the measurements.

The dynamic engineering stress σ , strain ε and strain rate $\dot{\varepsilon}$ were determined from the strain wave data recorded during the SHPB tests using:

$$\sigma(t) = \frac{E_b A_b}{A_s} \varepsilon_T(t) \quad (4)$$

$$\varepsilon(t) = -\frac{2C_0}{L} \int_0^t \varepsilon_R(t) dt \quad (5)$$

$$\dot{\varepsilon}(t) = -\frac{2C_0}{L} \varepsilon_R(t) \quad (6)$$

where E_b and C_0 are the Young's modulus and elastic wave speed of the bar, A_b and A_s are the cross-sectional areas of the bar and the specimen, respectively, t is the instantaneous time and L is the length of the test specimen. The converted engineering stress-strain curves from the SHPB tests are shown in Fig. 14, where the quasi-static compressive stress-strain curves are also provided. As the strain rate increases from quasi-static levels to approximately 2000 s^{-1} for the EN 1.4678 stainless steel and 1600 s^{-1} for the EN 1.4307 stainless steel, their yield strengths nearly double, indicating significant strain rate sensitivity. The dynamic stress-strain curves at higher strain rates extend further than those at lower strain rates, primarily because achieving higher strain rates in the SHPB tests requires greater impact energy from the striker bar, leading

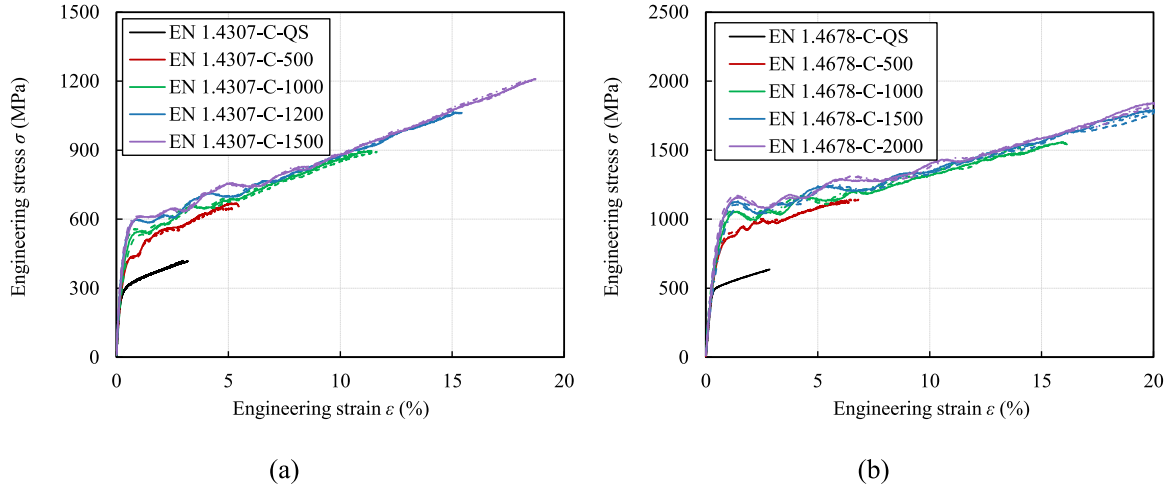


Fig. 14. Engineering stress-strain curves obtained from SHPB tests and quasi-static compressive tests.

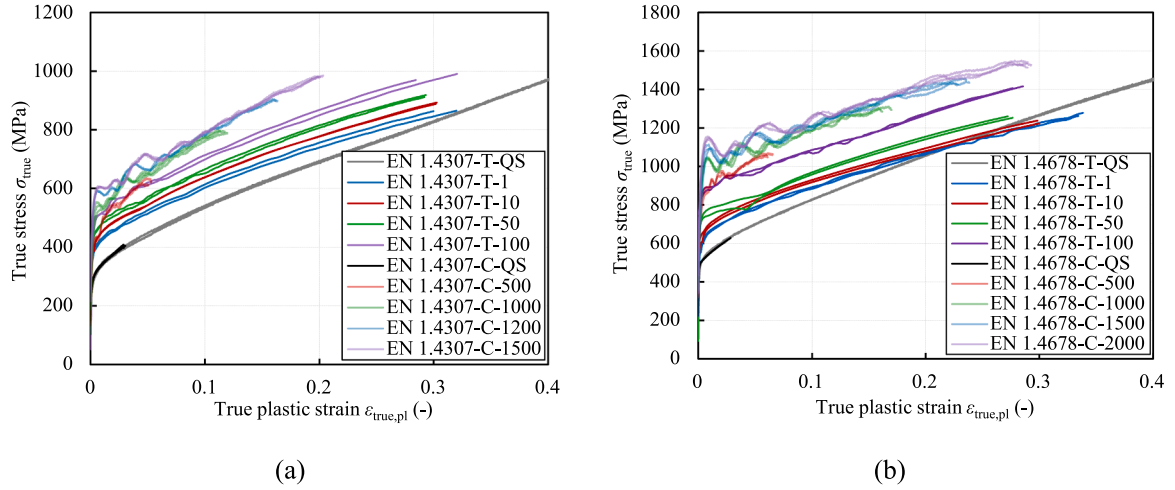


Fig. 15. True stress-plastic strain curves of (a) EN 1.4307 and (b) EN 1.4678 stainless steel at various strain rates, with the data after f_u removed for the tensile test results.

to larger compressive deformations and higher final strains in the specimens. Note that the final recorded strain does not correspond to the ultimate strain, as the dynamic compressive stress typically continues to increase with strain without exhibiting a distinct peak. All the key

mechanical properties obtained from the high strain rate tests are summarised in Tables 4 and 5.

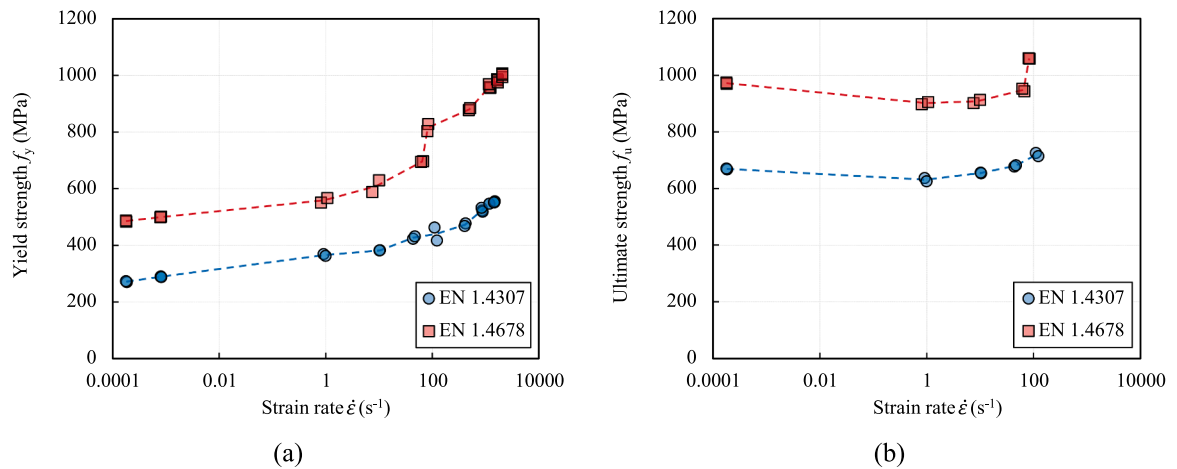


Fig. 16. Variation of (a) yield strength and (b) ultimate strength with strain rate.

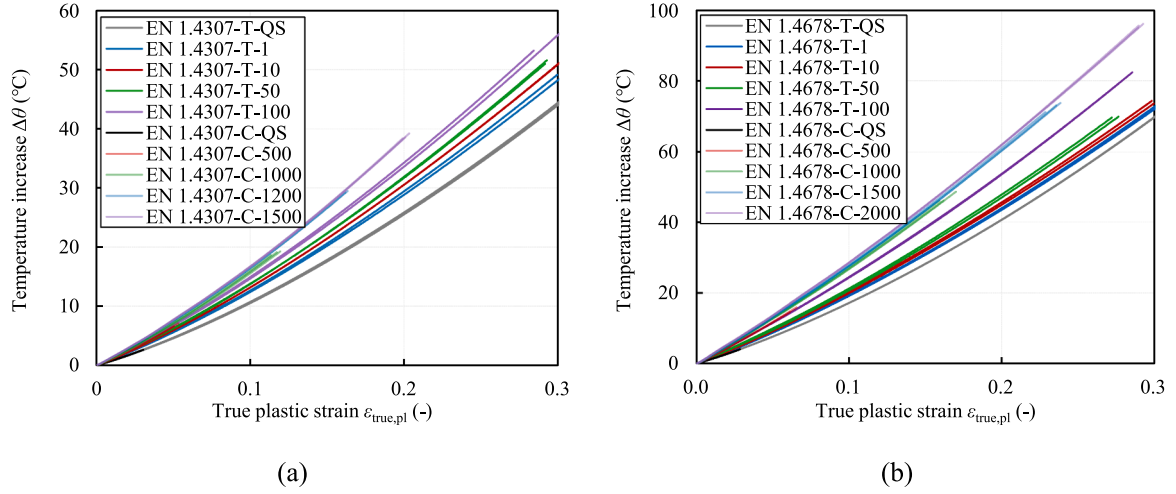


Fig. 17. Temperature increases caused by plastic deformation in the tested (a) EN 1.4307 and (b) EN 1.4678 stainless steel coupons.

3.5. True stress-plastic strain curves

True stress-plastic strain relationships provide critical insight into the plastic deformation behaviour of a material beyond its yield point, and serve as a key basis for numerical simulations. The true stress σ_{true} , true strain ϵ_{true} and true plastic strain $\epsilon_{\text{true,pl}}$ values were computed from the measured engineering stress-strain data using Eqs. (7)–(9)

$$\sigma_{\text{true}} = \sigma(1 + \epsilon) \quad (7)$$

$$\epsilon_{\text{true}} = \ln(1 + \epsilon) \quad (8)$$

$$\epsilon_{\text{true,pl}} = \epsilon_{\text{true}} - \epsilon_{\text{el}} \quad (9)$$

where the engineering strain ϵ and elastic strain ϵ_{el} (equal to σ_{true}/E) are negative in compression. Note that in the case of tensile tests, these equations are only valid up to the onset of necking, and accurate characterisation of post-necking behaviour requires additional volumetric corrections. The true stress-plastic strain ($\sigma_{\text{true}}-\epsilon_{\text{true,pl}}$) curves of the studied stainless steels at all examined strain rates are presented in Fig. 15, showing an approximately parallel uplift trend under dynamic loading conditions. The true stress-plastic strain curves from the quasi-static tensile and compressive tests were found to be similar for both the EN 1.4307 and EN 1.4678 stainless steel grades; only the measured quasi-static tensile results were therefore used as the benchmark for the subsequent strain rate sensitivity analysis.

3.6. Strain rate effect on strengths

3.6.1. Yield and ultimate strengths

The variation of the measured yield and ultimate strengths with strain rates are presented in Fig. 16, and the corresponding dynamic increase factors (DIF_y and DIF_u) are plotted against the strain rates on a logarithmic scale in Fig. 16. A curve representing the average trend of the measured test data for each mechanical property is also shown. The strain rate was observed to have a significant influence on the yield strength of both EN 1.4307 and EN 1.4678 stainless steels, with the high-strength EN 1.4678 grade exhibiting lower sensitivity to strain rate compared to the normal-strength EN 1.4307 grade, as shown in Fig. 16 (a). This finding is consistent with previous studies [7,15].

The ultimate strengths of both stainless steel grades also showed strain rate dependence, initially decreasing from the quasi-static level ($\dot{\epsilon}=0.00018 \text{ s}^{-1}$) to 1 s^{-1} , followed by a gradual increase with increasing strain rate. The decline in ultimate strength is attributed to the thermal softening caused by adiabatic heating and the associated weakening of strain hardening due to the suppression of austenite-to-martensite phase

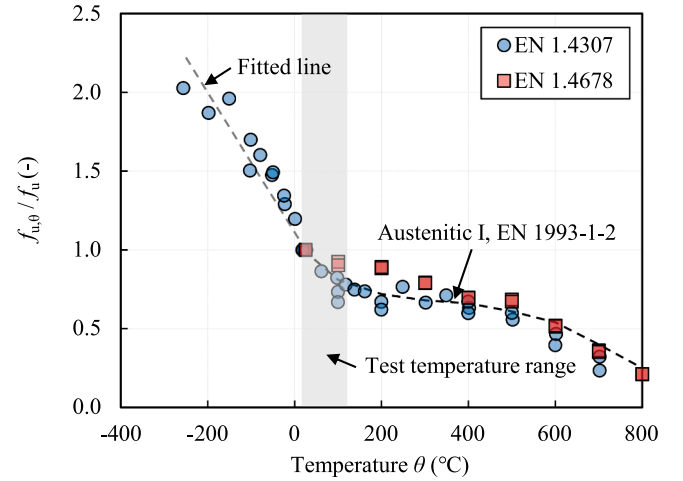


Fig. 18. Variation of ultimate strength with temperature from previous studies.

transformation. During plastic deformation, the generated heat has insufficient time to dissipate into the air (i.e., nearly adiabatic conditions) [13,43], leading to a temperature increase in the test specimen, which can be estimated using [44]

$$\Delta\theta = \beta \frac{\int_0^{\epsilon_{\text{true}}} \sigma_{\text{true}} d\epsilon_{\text{true,pl}}}{\rho c_p} \quad (10)$$

where $\Delta\theta$ is the temperature increase, σ is the true stress, ρ is the density of the material, c_p is the specific heat, equal to $466 \text{ J/(kg}^\circ\text{C)}$ for stainless steel, and β is a coefficient representing the fraction of plastic work converted to heat, taken as 0.9, as suggested by [13,45]. The estimated temperature increase is plotted against the true plastic strain in Fig. 17 (a) and Fig. 17(b) for EN 1.4307 and EN 1.4678 stainless steel, respectively. At a true plastic strain of 0.3, the temperature increases in the EN 1.4307 and EN 1.4678 stainless steel coupons tested at nominal strain rates of 100 s^{-1} were approximately 56°C and 87°C , respectively. At this level of temperature increase, the ultimate strengths $f_{u,\theta}$ of the examined stainless steel grades or comparable alloys were reduced by approximately 15%, as indicated by previous experimental studies [46–48] – see Fig. 18. When the strain rate exceeded about 50 s^{-1} , strain rate effects became dominant, with a monotonic increase in ultimate strength of both stainless steel grades. In the early stages of each of the dynamic tests, heat generation is minimal due to the low plastic strains (see Fig. 17), making thermal softening effects negligible compared to

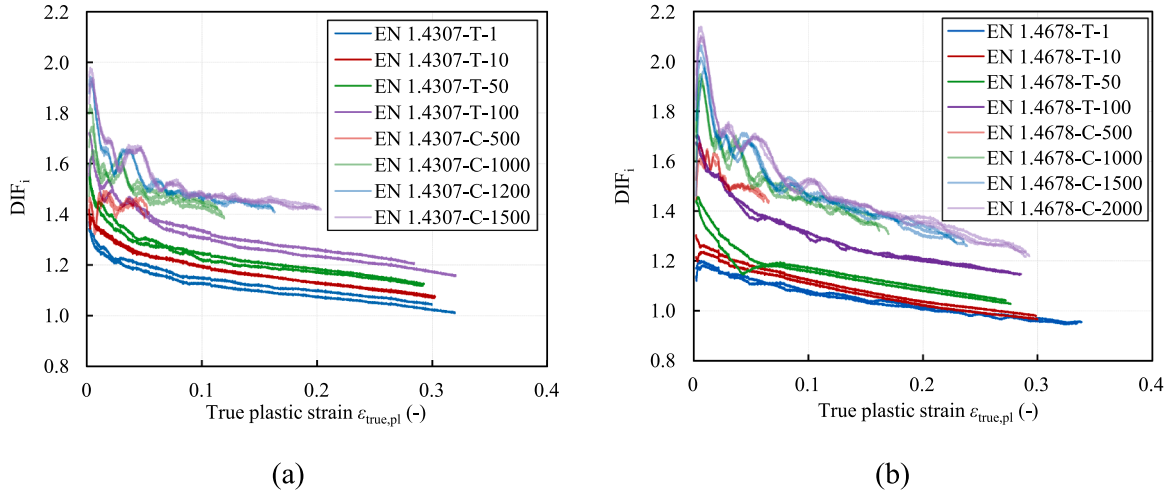


Fig. 19. DIF_i values of all test specimens during plastic deformation: (a) EN 1.4307 and (b) EN 1.4678 stainless steel.

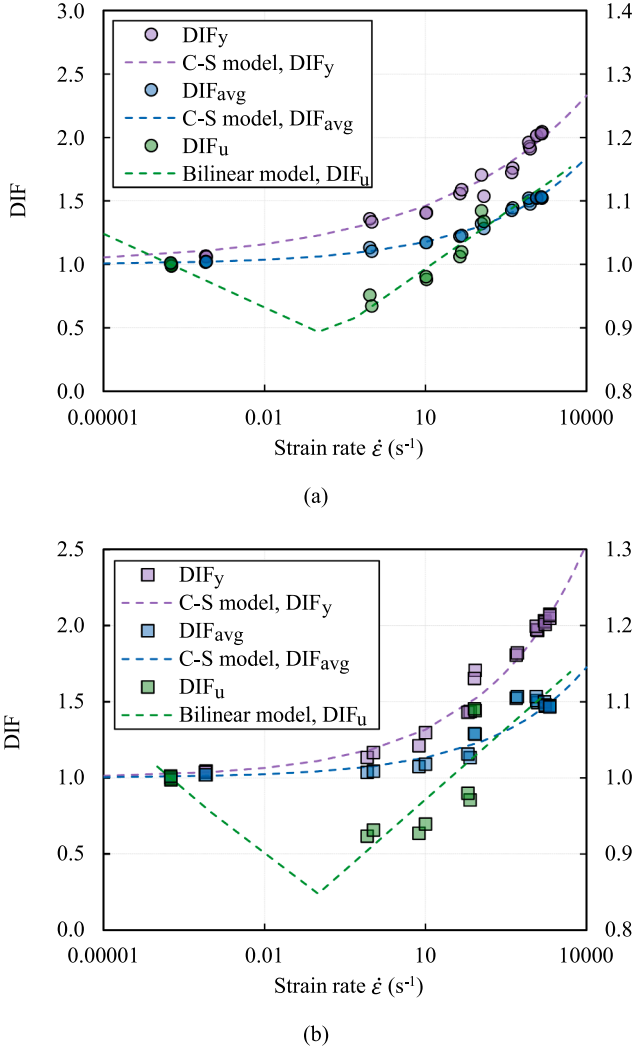


Fig. 20. Measured DIF values and fitted model for (a) EN 1.4307 and (b) EN 1.4678 stainless steel.

strain rate effects, thus leading to a continuous increase in yield strength with increasing strain rate.

3.6.2. Dynamic increase factors

The ratios of the dynamic stresses to the corresponding quasi-static stresses DIF_i of all test specimens during plastic deformation are presented in Fig. 19(a) for the EN 1.4307 stainless steel and Fig. 19(b) for the EN 1.4678 stainless steel. The DIF_i values were observed to decrease with increasing plastic strain, resulting in higher DIF_y values compared to DIF_u values. The dynamic increase factors for the yield strength, the ultimate strength and the overall flow curve are plotted against the measured strain rates in Fig. 20. As the strain rate increases, the DIF_y values increase monotonically, whereas the DIF_u values exhibit a bilinear (first reducing and then increasing) trend, for the reasons explained in Section 3.6.1. The dynamic increase factor DIF_{avg} of each coupon, which is defined as the average ratio of the DIF_i values, are summarised in Tables 4 and 5, and employed to quantify the overall increase of the plastic flow curve under dynamic conditions. It can be seen that the DIF_y values are 12 %–47 % higher than DIF_{avg} values for the EN 1.4307 stainless steel and 9 %–37 % higher for the EN 1.4678 stainless steel, indicating the limitation of using DIF_y values in representing the strain rate effect across the full range of the stress-strain curves.

3.7. Strain rate effect on ultimate and fracture strains

The ultimate strains ϵ_u and the fracture strains ϵ_f of the investigated EN 1.4307 and EN 1.4678 stainless steels are summarised in Tables 4 and 5 and are graphically presented in Fig. 21. The ultimate and fracture strains cannot be obtained from the quasi-static compressive or SHPB tests, so only the test results for the tensile coupons are presented herein. The dynamic increase factors for ultimate strains and fracture strains are plotted against the strain rates in Fig. 22. Both the ϵ_u and ϵ_f values of the EN 1.4307 stainless steel decreased significantly with increasing strain rate, indicating pronounced strain rate embrittlement. For the EN 1.4678 stainless steel, although the ultimate strains ϵ_u also decreased from 0.55 to approximately 0.35 as the test strain rate increased from 0.00018 s^{-1} to around 80 s^{-1} , the fracture strains ϵ_f remained relatively constant, fluctuating within a narrow range of 0.57–0.62.

4. Dynamic constitutive modelling

In this section, the applicability of existing dynamic constitutive models to the examined stainless steel grades (EN 1.4307 (304 L) and EN 1.4678 (Forta H500)) is first evaluated. Specifically, the Cowper–Symonds (C–S) and Johnson–Cook (J–C) models were assessed and modified for the description of the dynamic stress-strain response of the tested stainless steels at quasi-static, intermediate and high strain rates.

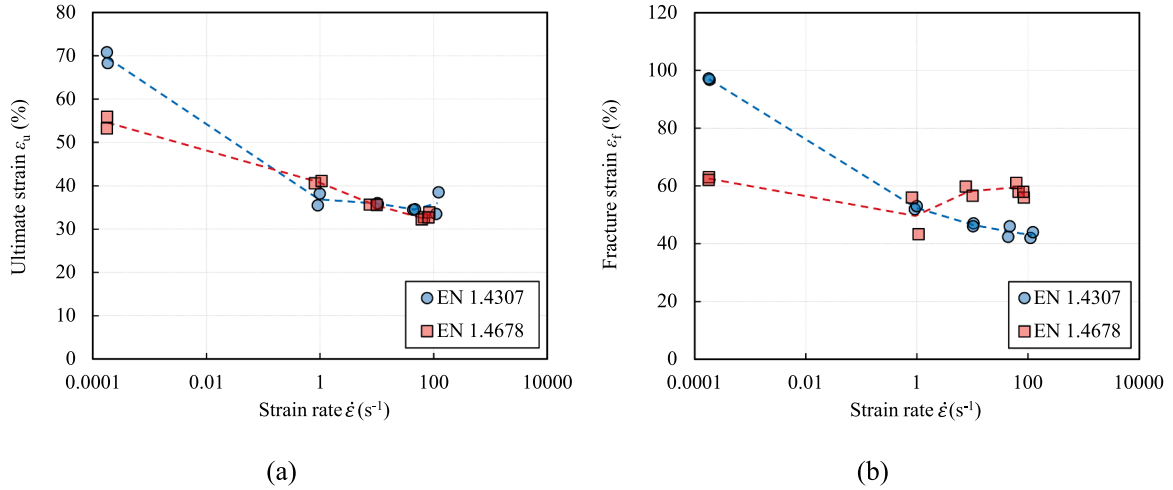


Fig. 21. Variation of (a) ultimate strains and (b) fracture strains with strain rates.

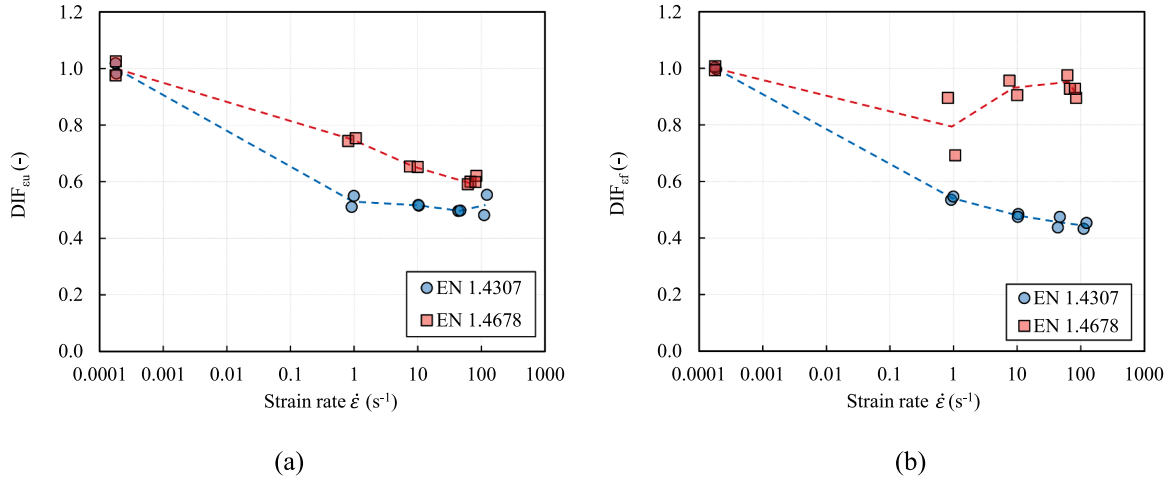


Fig. 22. Variation of dynamic increase factors for (a) ultimate strains and (b) fracture strains with strain rates.

Table 6

Fitted DIF parameters for the examined stainless steels.

Material	DIF _y		DIF _{avg}		DIF _u				
	<i>D</i>	<i>p</i>	<i>D</i>	<i>p</i>	$\dot{\epsilon}_b$	<i>u</i> ₁	<i>u</i> ₂	<i>u</i> ₃	<i>u</i> ₄
EN 1.4307	1560	6.5	21350	4.4	0.16	-1.68×10^{-2}	0.85	2.68×10^{-2}	0.93
EN 1.4678	1530	4.4	36678	4.1	0.08	-2.60×10^{-2}	0.78	2.55×10^{-2}	0.91
All grades (collected data + present study)	1730	4.0	9547	3.1	0.20	-1.14×10^{-2}	0.91	2.59×10^{-2}	0.97

A generalised dynamic constitutive model is also established to cover a broad range of stainless steel grades with different nominal yield strengths and strain rates, on the basis of collected test data from previous studies and the test results generated in the present study.

4.1. Models for DIF

The Cowper–Symonds (C–S) model is widely used to describe the dynamic mechanical properties of metallic alloys, and is expressed as [17]

$$\text{DIF}_* = \frac{f_{*,d}}{f_*} = 1 + \left(\frac{\dot{\epsilon}}{D} \right)^{1/p} \quad (11)$$

where DIF_{*} represents the dynamic increase factor for the defined stress parameter f_* , with the corresponding dynamic stress denoted as $f_{*,d}$, $\dot{\epsilon}$ is

the strain rate and *D* and *p* are material coefficients. The *D* and *p* values in the C–S model for DIF_y and DIF_{avg} were determined by fitting to the test results of the examined stainless steels through nonlinear least-squares regression analysis and are presented in Table 6. The experimental DIF_y and DIF_{avg} values, as well as the DIF_u values, are compared with the DIF values from the C–S model (or proposed model for DIF_u) in Fig. 20. The DIF_u curve of the examined stainless steel exhibited a bilinear trend with a transition strain rate of around 0.1–0.2 s^{−1}; this behaviour cannot be accurately described by the C–S model. Both the descending and ascending segments of the curve on a natural logarithmic scale showed linear characteristics; thus, empirical bilinear models are proposed to predict the dynamic increase factors for the ultimate strength of the examined stainless steels, as expressed by

Table 7

Summary of dynamic tests on stainless steels.

No.	Type	Grade	$f_{y,static}$ (MPa)	$\dot{\epsilon}$ (s ⁻¹)	References	Test setup
1	Austenitic	301LN (1.4318)	312	0.0003–200	Talonen et al. (2005) [39]	MTS 810 high-speed tensile machine
2	Austenitic	304 (1.4301)	332	0.0003–200	Talonen et al. (2005) [39]	
3	Austenitic	301LN (1.4318)	496	0.0003–200	Talonen et al. (2005) [39]	
4	Austenitic	304 (1.4301)	512	0.0003–200	Talonen et al. (2005) [39]	
5	Austenitic	309 (1.4828)	291	0.000125–400	Lichtenfeld et al. (2006) [49]	MTS 810 high speed tensile machine
6	Austenitic	304 L (1.4307)	300	0.000125–400	Lichtenfeld et al. (2006) [49]	
7	Austenitic	316 L (1.4404)	196	0.001–7500	Lee et al. (2007) [50]	MTS 810 tensile machine + SHPB
8	Austenitic	304LN (1.4311)	340	0.0001–1	Das & Tarafder (2009) [51]	Instron 8862 tensile machine
9	Austenitic	304 (1.4301)	538	0.001–1000	Cadoni et al. (2012) [52]	Electromechanical tensile machine
10	Austenitic	301 L (1.4319)	302	0.0000033–1000	Tsuchida et al. (2013) [53]	Electromechanical tensile machine
11	Austenitic	304 (1.4301)	308.5	0.0000033–100	Tsuchida et al. (2013) [53]	
12	Lean duplex	Duplex 2101 (1.4162)	517.7	0.0000033–1000	Tsuchida et al. (2014) [16]	
13	Duplex	Duplex 2205 (1.4462)	590.0	0.0000033–1000	Tsuchida et al. (2014) [16]	
14	Austenitic	304 L (1.4307)	306.1	0.089–33.6	Paik et al. (2017) [54]	Dynamic tensile machine
15	Ferritic	CR5 (1.4104)	160	0.005–500	Alturk (2018) [15]	Dynamic tensile machine
16	Austenitic	201LN (1.4372)	320	0.005–500	Alturk (2018) [15]	
17	Ferritic+martenitic	DP590	365	0.005–500	Alturk (2018) [15]	
18	Ferritic+martenitic	DP980	715.0	0.005–500	Alturk (2018) [15]	
19	Ferritic+martenitic+austenitic	QP980	690.0	0.005–500	Alturk (2018) [15]	
20	Austenitic	304 L (1.4307)	280	0.001–1000	Sunil & Kapoor (2020) [55]	SHPB
21	Martensitic	17-4PH (1.4542)	541–568	0.01–10	Wang et al. (2020) [56]	Zwick-Roell HTM5020 high speed tensile machine
22	Austenitic	304 L (1.4307)	190.2	0.0001–3155	Jin et al. (2021) [14]	Fast MTS high-rate tensile machine + Drop-Hopkinson bar
23	Austenitic	304 (1.4301)	240–255	0.001–100	Seo et al. (2022) [40]	High-speed tensile machine
24	Austenitic	304 (1.4301)	248	0.001–1000	Seo et al. (2022) [57]	High-speed tensile machine
25	Austenitic	304 L (1.4307)	278	0.001–100	Seo et al. (2022) [57]	
26	Austenitic	316 L (1.4404)	255	0.0004–10	Seo et al. (2022) [57]	
27	Austenitic	304 (1.4301)	298	0.0067–6212	Jia et al. (2021) [11]	Zwick-Roell HTM5020 high speed tensile machine + SHTB
28	Austenitic	316 (1.4401)	267	0.0067–4450	Jia et al. (2021) [11]	
29	Austenitic	304 (1.4301)	297	0.001–100	Xu et al. (2019) [58]	Zwick-Roell HTM5020 high speed tensile machine
30	Martensitic	17-4PH (1.4542)	937–1355	0.001–1000	Lebrun (2014) [59]	SHTB
31	Austenitic	A4-70 (1.4401)	639.6	0.008–160	SS bolt [60]	Zwick-Roell HTM5020 high speed tensile machine + SHPB
32	Duplex	DX109 (1.4462)	768.7	0.008–110	SS bolt [60]	
33	Austenitic	304 L (1.4307)	271.4	0.00018–1500	Present study	Zwick-Roell HTM5020 high speed tensile machine + SHPB
34	Austenitic	H500 (1.4678)	485.4	0.00018–2000	Present study	
Summary		17 grades	160–1355	0.0001–7500	18 references and present study	

$$DIF_u = \begin{cases} u_1 \ln(\dot{\epsilon}) + u_2 & \dot{\epsilon} < \dot{\epsilon}_b \\ u_3 \ln(\dot{\epsilon}) + u_4 & \dot{\epsilon} \geq \dot{\epsilon}_b \end{cases} \quad (12)$$

where u_1 to u_4 are four material coefficients of the model, and $\dot{\epsilon}_b$ is the strain rate corresponding to the transition point, which can be approximated as 0.16 s⁻¹ and 0.08 s⁻¹ for the examined EN 1.4307 and EN 1.4678 stainless steels, respectively.

Additional dynamic stress-strain data for a wide range of stainless steel grades have been collected from previous studies [11,14–16,39,40,49–60] and are summarised in Table 7, where the studied stainless steel types and grades, strain rates and test setup are provided. The collected DIF_y and DIF_u values, together with those from the present study, are graphically presented in Fig. 23. Among these studies, the full stress-strain curves have been reported in [11,14,16,39,40,42,49–51,53,60], and the derived DIF_{avg} values are plotted against the test strain rates in Fig. 23. The full dataset contained 184 stress-strain curves for stainless steels with yield strengths ranging from 190 to 770 MPa and strain

rates spanning 0.000033–7500 s⁻¹, including the test data for EN 1.4307 and EN 1.4678 stainless steels presented in this study and reported in [60]. The C–S curves fitted to all the DIF_y and DIF_{avg} data, and the fitted bilinear model based on all DIF_u data, are also presented in Fig. 23, and the corresponding material coefficients are given in Table 6.

The trend of the DIF_y curves for stainless steels with different yield strengths exhibited different levels of strain rate sensitivity, with higher strength stainless steel exhibiting lower sensitivity to strain rate, as seen for carbon steels in [7]. Thus, an empirical generalised strain-rate effect model for DIF_y , inspired by the C–S model but considering the dependency on both strain rate and yield strength, is proposed based on the collected and generated experimental data, as expressed by:

$$DIF_y = 1 + \left(\frac{\dot{\epsilon}}{D_y} \right)^{1/p_y} \quad (13)$$

where

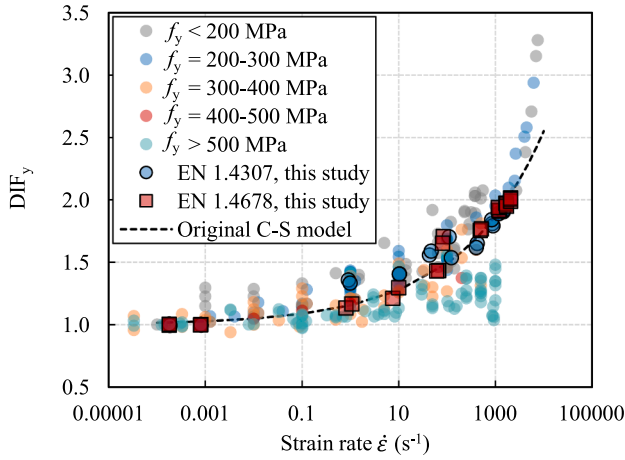
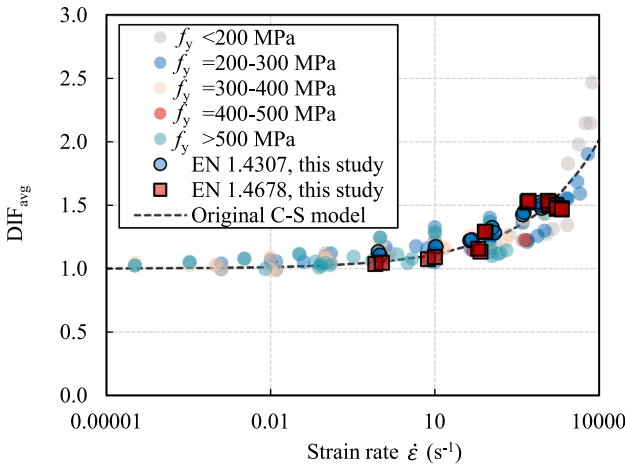
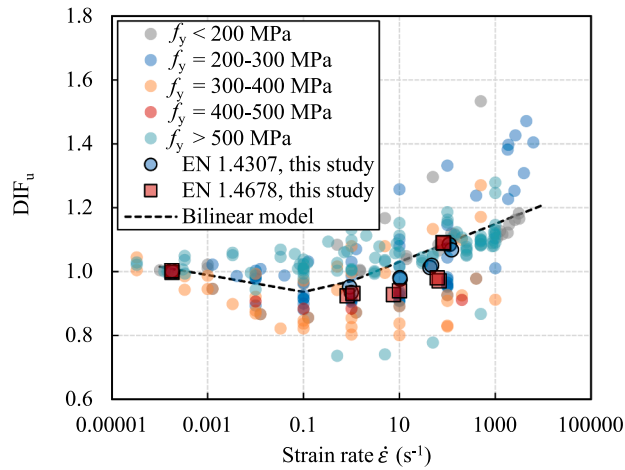
(a) DIF_y (b) DIF_{avg} (c) DIF_u

Fig. 23. Dynamic experimental data and strain-rate effect model for (a) DIF_y , (b) DIF_{avg} and (c) DIF_u .

$$D_y = 650 \left(\frac{f_y}{235} \right)^{2.5} \quad (14)$$

$$p_y = 4.7 \left(\frac{f_y}{235} \right)^{-0.36} \quad (15)$$

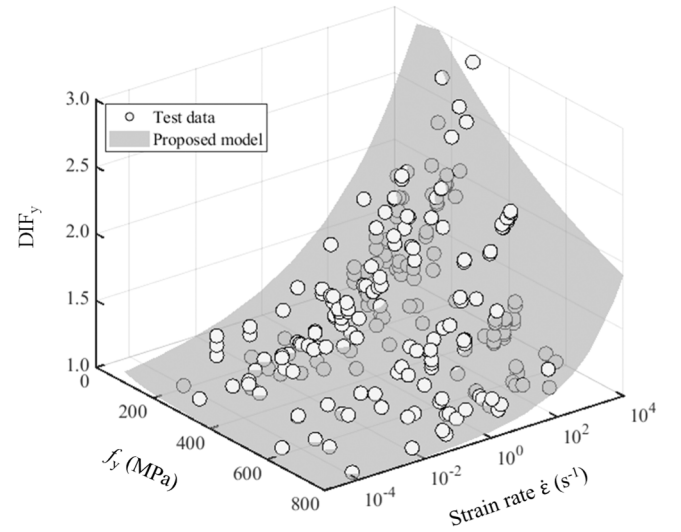


Fig. 24. Visualisation of DIF_y test data and proposed model as a function of yield strength and strain rate.

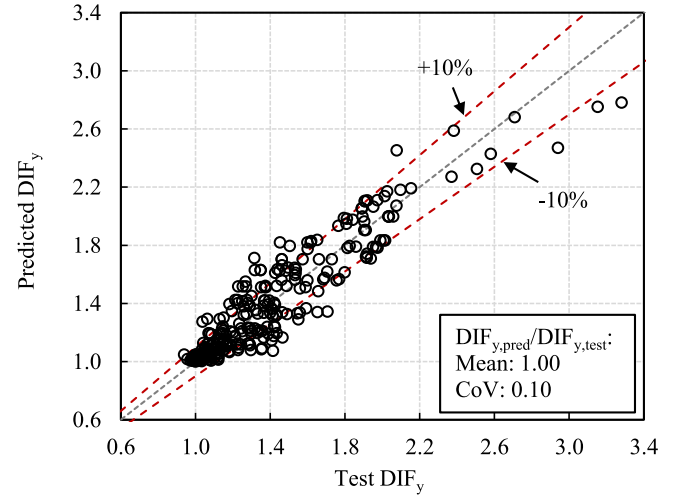


Fig. 25. Comparison between test and predicted DIF_y values.

Fig. 24 presents a 3D comparison between the experimental DIF_y values and the predictions from the proposed model, as a function of yield strength and strain rate. The predicted and measured DIF_y values from the full dataset are compared in Fig. 25, where the majority of the test data are well predicted by the proposed model. Similarly, an empirical expression for DIF_{avg} is proposed based on the collected test data and the results from this study, as given by

$$DIF_{avg} = 1 + \left(\frac{\dot{\epsilon}}{D_{avg}} \right)^{1/p_{avg}} \quad (16)$$

where

$$D_{avg} = 8130 \left(\frac{f_y}{235} \right)^{2.1} \quad (17)$$

$$p_{avg} = 2.9 \left(\frac{f_y}{235} \right)^{0.5} \quad (18)$$

All DIF_{avg} values are plotted against the yield strength and the strain rate in Fig. 26, together with the proposed model. The experimental and predicted DIF_{avg} values are compared in Fig. 27, indicating that the

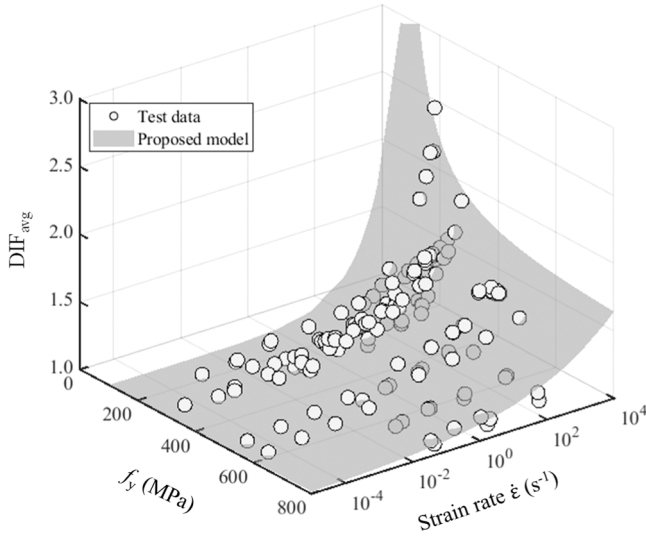


Fig. 26. Visualisation of DIF_{avg} test data and proposed model as a function of yield strength and strain rate.

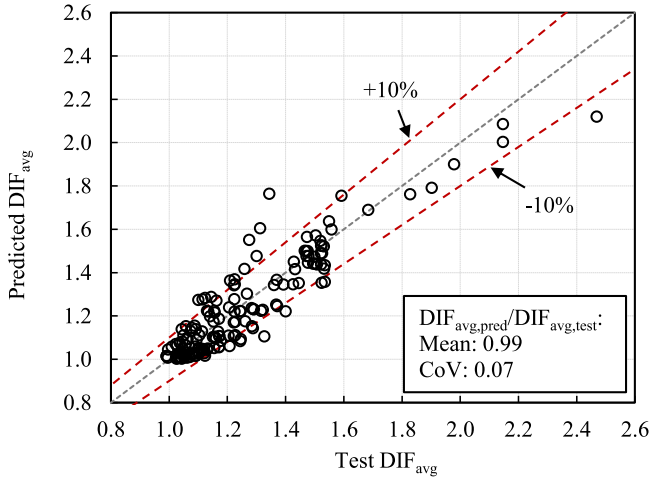


Fig. 27. Comparison between test and predicted DIF_{avg} values.

proposed DIF_{avg} model can provide accurate predictions for the examined EN 1.4307 and EN 1.4678 stainless steels from the present study, as well as for other stainless steels reported in the literature [11,14,16,39,40,42,49–51,53,60].

4.2. Modified Johnson–Cook model

The Johnson–Cook model, incorporating the effects of strain hardening, strain rate and temperature, is given by:

$$\sigma_{true} = (A + B\epsilon_{true,pl}^n)[1 + C\ln(\dot{\epsilon}/\dot{\epsilon}_0)](1 - T^{*m}) \quad (19)$$

$$T^{*} = (T - T_r)/(T_m - T_r) \quad (20)$$

where σ_{true} is the true stress, $\epsilon_{true,pl}$ is the true plastic strain, n is the strain hardening exponent, $\dot{\epsilon}$ and $\dot{\epsilon}_0$ are the dynamic strain rate and the reference strain rate, respectively, T^{*} is a dimensionless temperature parameter, T , T_r and T_m are the test temperature, room temperature and melting temperature, respectively, and A , B , n , C , and m are material coefficients to be calibrated. The first term $A + B\epsilon_{true,pl}^n$ describes the effect of strain hardening on the true stress-plastic strain curve at the

Table 8

Fitted Johnson–Cook model parameters for EN 1.4307 and EN 1.4678 stainless steels.

Material	$\dot{\epsilon}_0$ (s ⁻¹)	A	B	n	C
EN 1.4307	1	371.1	1070.9	0.64	$C = 5.4 \times 10^{-4} \ln^2(\dot{\epsilon}/\dot{\epsilon}_0) - 1.3 \times 10^{-4} \ln(\dot{\epsilon}/\dot{\epsilon}_0) + 1.4 \times 10^{-2}$
EN 1.4678	1	596.2	1404.1	0.68	

reference strain rate. The second term $1 + C\ln(\dot{\epsilon}/\dot{\epsilon}_0)$ represents the strain rate effect under dynamic loading, while the third term $1 - T^{*m}$ reflects the temperature-induced softening effect and can be neglected in room temperature tests. Note that the third term $1 - T^{*m}$ is not able to capture the adiabatic heating that is discussed in Section 3.6.1. Instead, the predictive models for DIF_y , DIF_{avg} and DIF_u in Section 4.1, derived from the test data, implicitly account for the temperature effects associated with high strain rates.

Various J–C model variants have been developed to improve its predictive accuracy, such as the J–C model in which C varies as a function of strain rate [9,11,61], a piecewise J–C model [13,62] and a combined J–C and C–S model in which the term $1 + C\ln(\dot{\epsilon}/\dot{\epsilon}_0)$ is replaced with $1 + (\dot{\epsilon}/D)^{1/p}$ [10]. In the present study, the values of A , B and n were first determined by fitting to the true stress-plastic strain data obtained at the reference strain rate of 1 s^{-1} , using a nonlinear least-squares method. An empirical formula for the coefficient C as a function of strain rate was then derived by nonlinear least-squares fitting to the test curves at various strain rates, as presented in Table 8. A comparison between the experimental true stress-plastic strain curves determined at different strain rates and the results predicted using the modified J–C model are shown in Fig. 28, together with the mean relative root mean square error (RMSE). For the EN 1.4307 stainless steel, good agreement is observed across the full strain range, while for the EN 1.4678 stainless steel, the model shows generally good agreement, although with reduced accuracy in the strain rate range of $50\text{--}500 \text{ s}^{-1}$. This confirms the capability of the modified model to accurately represent the strain rate sensitivity and plastic deformation behaviour of the examined stainless steels under dynamic loading conditions.

4.3. Generalised dynamic Ramberg–Osgood model

4.3.1. Static material model

The two-stage Ramberg–Osgood model set out in EN 1993-1-14 [63], the development of which is described in [37,64–67], is widely used to characterise the nonlinear stress-strain behaviour of stainless steel under quasi-static loading and is expressed by:

$$\epsilon = \begin{cases} \frac{\sigma_s}{E} + 0.002 \left(\frac{\sigma_s}{f_y} \right)^n & \text{for } \sigma_s \leq f_y \\ \frac{\sigma_s - f_y}{E_{p0.2}} + \left(\epsilon_u - \epsilon_{p0.2} - \frac{f_u - f_y}{E_{p0.2}} \right) \left(\frac{\sigma_s - f_y}{f_u - f_y} \right)^{m_u} + \epsilon_{p0.2} & \text{for } f_y < \sigma_s \leq f_u \end{cases} \quad (21)$$

where σ_s and ϵ denote the engineering stress and strain, respectively, E is the Young's modulus, $E_{p0.2}$ and $\epsilon_{p0.2}$ are the tangent modulus and total strain at the yield (0.2 % proof) strength f_y , and n and m_u are the strain hardening exponents that define the roundness of the first and second stages of the stress-strain curve. As an alternative to the second stage of the material model, Eq. (22), proposed by Gardner and Ashraf [38], can be used, which generally provides a more accurate representation of the stress-strain response up to approximately 10 % strain, making it suitable for modelling stainless steel structural elements experiencing instability [68], while Eq. (21) is more well-suited for modelling high strain scenarios such as connections [69]. In Eq. (22), $\epsilon_{p1.0}$ is the total

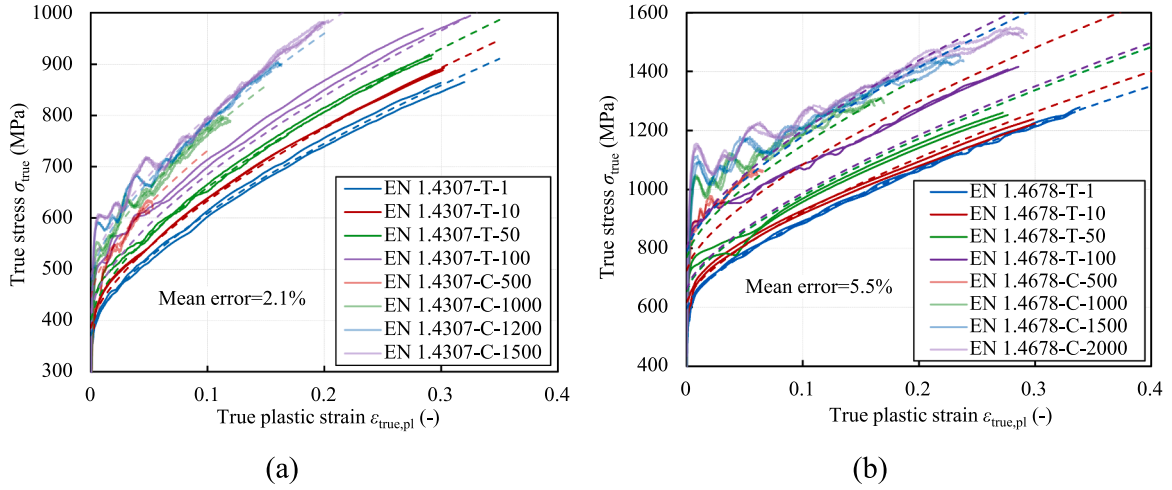


Fig. 28. Comparison of true stress-plastic strain curves obtained from tests with fitted curves from the modified Johnson–Cook model: (a) EN 1.4307 and (b) EN 1.4678 stainless steel.

strain at the 1.0 % proof strength $f_{p1.0}$, and $m_{1.0}$ is an exponent that ensures the second stage of the model passes through the 1.0 % proof strength. A more detailed review of two-stage Ramberg–Osgood material models can be found in [38,65].

$$\varepsilon = \frac{\sigma_s - f_y}{E_{p0.2}} + \left(\varepsilon_{p1.0} - \varepsilon_{p0.2} - \frac{f_{p1.0} - f_y}{E_{p0.2}} \right) \left(\frac{\sigma_s - f_y}{f_{p1.0} - f_y} \right)^{m_{1.0}} + \varepsilon_{p0.2} \quad \text{for } f_y < \sigma_s \leq f_u \quad (22)$$

4.3.2. Proposed dynamic material model for stainless steel

A generalised dynamic constitutive model for stainless steels, considering the effect of the strain rate and the yield strength of material, is proposed. The model incorporates the average dynamic increase factor DIF_{avg} to scale the static true stress-plastic strain curve, as expressed by Eq. (23), where $\sigma(\varepsilon)$ and $\sigma_s(\varepsilon)$ represent the dynamic and static true stress-plastic strain curves, respectively, and $DIF_{avg}(\dot{\varepsilon}, f_y)$ denotes the proposed strain-rate effect model, as expressed by Eq. (16).

$$\sigma(\varepsilon) = \sigma_s(\varepsilon) \cdot DIF_{avg}(\dot{\varepsilon}, f_y) \quad (23)$$

The static engineering stress-strain curve of the stainless steel, as expressed by Eq. (21) or Eq. (22), is converted into the true stress-plastic strain curve using Eqs. (7)–(8)(9), and then scaled by the strain-rate effect model for DIF_{avg} to generate the dynamic stress-strain flow curve for use in dynamic finite element analysis. The two-stage Ramberg–Osgood model is widely used under static conditions and is directly related to the key mechanical properties (E , f_y and f_u) and the fitted parameters (n and m). The strain rate effect is incorporated through a modified Cowper–Symonds model, where average dynamic increase factors are employed to capture the enhancement of the full stress-strain curves rather than discrete points at f_y or f_u , and four fitted constants are used to consider both the strain rate and the yield strength of the stainless steel. Fig. 29 shows comparisons between experimental and predicted dynamic true stress-plastic strain curves for stainless steels with different yield strengths, demonstrating the accuracy of the proposed model across a wide range of strain rates and stainless steel grades. Future work can be dedicated to expanding the dataset and to assess the applicability of the proposed model under more extreme conditions.

4.4. Summary of proposals

The proposed model to describe the dynamic stress-strain (σ - ε) response of stainless steel employs the static two-stage Ramberg–Osgood

model:

$$\varepsilon = \begin{cases} \frac{\sigma_s}{E} + 0.002 \left(\frac{\sigma_s}{f_y} \right)^n & \text{for } \sigma_s \leq f_y \\ \frac{\sigma_s - f_y}{E_{p0.2}} + \left(\varepsilon_u - \varepsilon_{p0.2} - \frac{f_u - f_y}{E_{p0.2}} \right) \left(\frac{\sigma_s - f_y}{f_u - f_y} \right)^{m_u} + \varepsilon_{p0.2} & \text{for } f_y < \sigma_s \leq f_u \end{cases} \quad (21)$$

with the dynamic stress $\sigma(\varepsilon)$ modified from that corresponding static values $\sigma_s(\varepsilon)$ through:

$$\sigma(\varepsilon) = \sigma_s(\varepsilon) \cdot DIF_{avg}(\dot{\varepsilon}, f_y) \quad (23)$$

where DIF_{avg} is the average dynamic increase factor, given by:

$$DIF_{avg} = 1 + \left(\frac{\dot{\varepsilon}}{D_{avg}} \right)^{1/p_{avg}} \quad (16)$$

in which the coefficients D_{avg} and p_{avg} are given by:

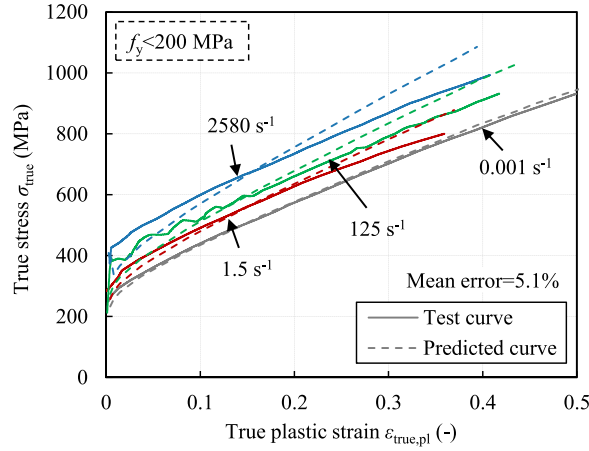
$$D_{avg} = 8130 \left(\frac{f_y}{235} \right)^{2.1} \quad (17)$$

and

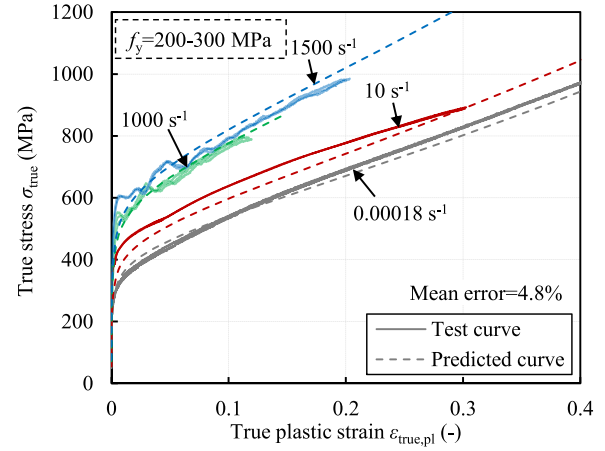
$$p_{avg} = 2.9 \left(\frac{f_y}{235} \right)^{0.5} \quad (18)$$

5. Conclusions

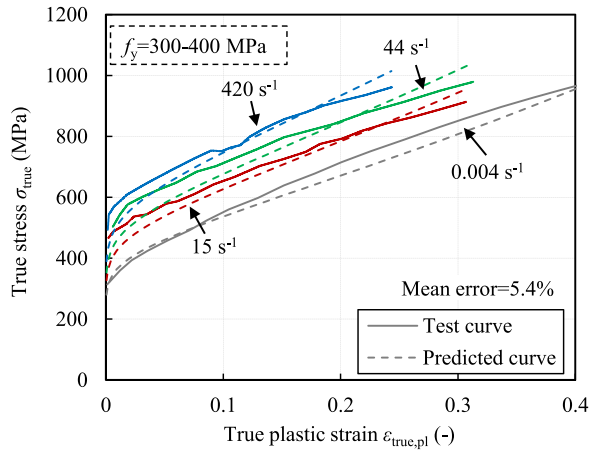
This paper presents an experimental investigation into the dynamic material behaviour of two austenitic stainless steel grades under quasi-static, intermediate and high strain rate conditions. Both tensile and compressive coupon tests were conducted under quasi-static loading for comparison with intermediate-rate tensile tests performed using a servo-hydraulic high-speed testing machine and high-rate compressive tests carried out using a split Hopkinson pressure bar (SHPB). The yield strength of the tested stainless steels exhibited significant strain-rate sensitivity, while the ultimate strength was less sensitive, partly due to strain rate effects being affected by strength loss due to the adiabatic heating. At a strain rate of 1500 s^{-1} , the dynamic increase factors for yield strength were approximately 1.90 for the EN 1.4307 stainless steel and 1.95 for the EN 1.4678 stainless steel. These experiments provide a consistent dataset of full stress-strain curves for both normal-strength



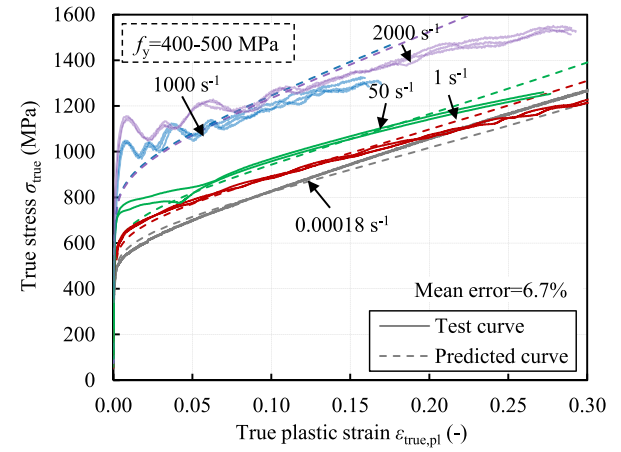
(a) EN 1.4307 stainless steel [14]



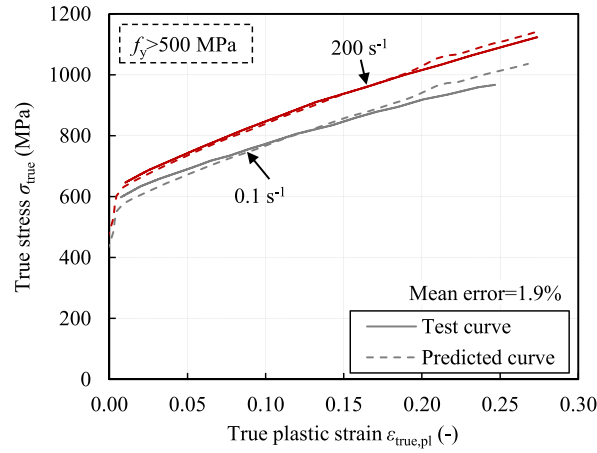
(b) EN 1.4307 stainless steel (present study)



(c) EN 1.4404 stainless steel [42]



(d) EN 1.4678 stainless steel (present study)



(e) EN 1.4301 2H stainless steel [39]

Fig. 29. Typical comparisons between experimental and predicted dynamic true stress-plastic strain curves.

and high-strength stainless steels across a wide range of strain rates, offering a robust basis for subsequent model calibration and development.

Following the experimental investigation, the existing Cowper–Symonds model and Johnson–Cook model were fitted and modified to characterise the dynamic behaviour of the examined stainless steels. To extend beyond the two tested grades, a comprehensive database of test results obtained from previous studies into the dynamic mechanical

properties of stainless steel was assembled. The database contained 184 individual experimental results on a wide range of stainless steel grades tested at strain rates between 0.0001 s^{-1} and 7500 s^{-1} . Based on the assembled dataset, a generalised constitutive model adapted from the two-stage Ramberg–Osgood representation of the static stress-strain curve and the Cowper–Symonds model for the average dynamic increase factor, to predict the strain-rate dependent stress-strain response of all stainless steels, as a function of strain rate and yield strength, was

proposed.

CRedit authorship contribution statement

Ruizhi Zhang: Methodology, Investigation, Data curation, Software, Formal analysis, Writing – original Draft, Visualisation. **Yong Zhu:** Methodology, Investigation, Software, Formal analysis. **Leroy Gardner:** Conceptualisation, Supervision, Writing – review & editing, Project administration, Funding acquisition.

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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Data availability

Data will be made available on request.

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