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Dynamic Tensile Testing of Ultrahigh Strength Hot Stamped Martensitic Steels

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Abstract

Tensile testing over strain rates of 0.001, 1, 100 and 200 s^{-1} was performed on three novel ultrahigh strength hot stamped martensitic steels, namely 38MnB5, 15MnCr5 and 25MnVB5, in addition to the conventional 'boron steel' for automotive hot stamping technologies, 22MnB5. Each steel generally demonstrated positive strain rate sensitivity (increasing tensile strength) with increasing strain rate from 0.001 to 1 s^{-1}, but negative strain rate sensitivity (decreasing tensile strength) with increasing strain rate from 1 to 200 s^{-1}. The notable exception to the above was 38MnB5, which demonstrated consistently increasing ultimate tensile strength across all four strain rates. Moreover, each steel generally demonstrated maximum elongation at strain rates of 100 or 200 s^{-1}. The response of 38MnB5 to increasing strain rate gave rise to significantly higher modulus of toughness (energy absorption) compared to 22MnB5 at the higher strain rates. It was concluded that 38MnB5 should provide superior 'anti intrusive' crash performance under low speed impact owing to significantly higher tensile strength, yet superior 'impact energy absorptive' crash performance under high speed impact owing to significantly higher modulus of toughness.

Key Words: dynamic tensile testing; martensitic; boron steel

1 Introduction

Hot stamped 'boron steels', namely 22MnB5, have become common place in the automotive body structure over the past 10-15 years [1], where they have been applied to the 'anti intrusive' structural body components, such as roof pillars; door, floor and roof reinforcements; and bumper beams [2]. Following hot stamping, martensitic 22MnB5 exhibits (quasi static) tensile properties in the order of 1200 MPa proof strength, 1500 MPa ultimate tensile strength and 6.0 % total elongation [1]. These ultrahigh strength tensile properties permit down gauging and vehicle weight reduction compared to the use of conventionally cold formed carbon manganese (CMn), high strength low alloy (HSLA) and dual phase (DP) steels, while maintaining adequate anti intrusive crash performance [3].

There has been copious research into novel steels for hot stamping and moreover, into development of the hot stamping process. Tokizawa et al. investigated the influence of manganese content and cooling rate on the tensile strength and toughness of hot stamped boron steel [4]. Hwang et al. investigated the relationship between austenisation temperature and quench hardenability of hot stamped boron steel [5]. Tungtrongpairoj et al. investiatgted the yield behaviour of boron steel at high temperature [6]. Yanagimoto and Oyamada investigated the mechanism of springback and its minimisation during warm and hot stamping [7]. Ikeuchi and Yanagimoto developed the 'hot forming simulator' as a tool for determining the influence of hot stamping process parameters on product properties [8]. Abbasi et al. investiagted the effect of strain rate and deformation temperature on hot stamped boron steel [9]. Naderi et al. investigated the affect of post quench tempering on hot stamped boron steel [10]. Naderi et al. investiagated a selection of boron and non boron hot stamped steels [11].

Quasi static tensile testing is defined by a strain rate of ≤ 0.008 s^{-1} [12]. Typically, the strain rate of 0.001 s^{-1} is used when obtaining the quasi static tensile properties of automotive steels. While tensile data produced under quasi static strain rates are certainly of value, higher strain rates, in the dynamic range of > 0.008 s^{-1} [12], are considered [13] to be more realistic and thus of greater relevance when evaluating automotive crash performance. For this reason, plentiful research has been conducted into the response of cold formed automotive steels to increasing strain rate in the dynamic range. Oliver et al. compared the microstructural changes between DP and transformation induced plasticity (TRIP) steels with increasing strain rate [14]. Beynon et al. investigated the work hardening behaviour of DP steels with increasing strain rate [15]. Bleck and Schael investigated the relationship between dynamic tensile properties and crash performance [16]. Miura et al. investigated the deformation behaviour of high strength steels under high strain rates [17]. However, there has been surprisingly little research into the response of hot stamped steels to increasing strain rate in the dynamic range. Bardelcik et al. demonstrated that water quenched 22MnB5 exhibited an increase to ultimate tensile strength of 20 MPa when increasing strain rate from 0.003 to 960 s^{-1} [18].

2 Experimental Details

2.1 Investigated Steels

Laboratory hot stamping was performed with ten experimental steels, in addition to the 22MnB5 control steel. The ten experimental steels included seven bespoke trial steels (laboratory produced) and three existing commercial steels (industrially produced). The seven experimental trial steels were all boron steels, featuring a base chemistry equal to 22MnB5. However, carbon content varied. Carbon contents included 0.15, 0.25, 0.29 and 0.38 wt %. Moreover, experimental trial steel 25MnB5 (0.25 wt % C) was further investigated with independent additions of molybdenum, vanadium and nickel. The three experimental commercial steels included 10MnCr5, 13MnCr5 and 15MnCr5.

During laboratory hot stamping, the blank was furnace heated to soak temperature. Nine soak time-temperature conditions were investigated for each steel (soak temperatures of 800, 850 and 900 ^{o}C; soak times of 1, 3 and 5 minutes). The blank was manually transferred from furnace to forming tool in ~ 10 s and hot stamped with mean cooling rate of more than -100 ^{o}C/s above 500 ^{o}C and mean cooling rate of more than -60 ^{o}C/s between 500 and 200 ^{o}C. Subsequently, the three most successful outcomes from laboratory hot stamping (determined by quasi-static tensile testing) were selected. The three most successful outcomes included three experimental steels with each treated to its as-determined optimal hot stamping soak condition. Collectively, these three experimental steels treated to their optimal hot stamping soak conditions met the three objectives of: 1) higher tensile strength-lower elongation (38MnB5); 2) lower tensile strength-higher elongation (15MnCr5); and 3) higher tensile strength-higher elongation (25MnVB5), compared to the 22MnB5 control steel. The three selected experimental steels, in addition to the 22MnB5 control steel (with each steel treated to its optimal hot stamping soak condition) were further evaluated with dynamic tensile testing. The optimal soak condition for 22MnB6, 25MnVB5, 38MnB5 and 15MnCr5 were respectively 1 min-850 ^{o}C, 3 min-850 ^{o}C, 5 min-850 ^{o}C and 5 min-850 ^{o}C. With the exception of a minute (and unintentional) volume fraction of retained γ-austenite, each steel exhibited a completely martensitic microstructure following hot stamping and prior to dynamic tensile testing. Chemical composition of each steel is presented in Table 1.

Table 1: Chemical compositions

	C	*Mn*	*Si*	*P*	*S*	*Cr*	*V*	*Nb*	*Mo*	*Ni*	*Ti*	*B*	*N*
22MnB5	0.225	1.229	0.211	0.018	0.008	0.289	0.000	0.000	0.001	0.000	0.037	0.0041	0.0049
25MnVB5	0.255	1.200	0.190	0.016	0.004	0.280	0.097	0.000	0.005	0.005	0.024	0.0030	0.0047
38MnB5	0.380	1.200	0.190	0.015	0.004	0.280	0.000	0.000	0.005	0.005	0.024	0.0030	0.0047
15MnCr5	0.135	2.100	0.290	0.014	0.001	0.620	0.000	0.018	0.015	0.000	0.000	0.0000	0.0065

2.2 Quasi Static and Dynamic Tensile Testing

Tensile testing was performed over strain rates of 0.001, 1, 100 and 200 s^{-1}. The quasi static strain rate of 0.001 s^{-1} was performed with the Zwick 1474 100 kN Electro-Mechanical tensile testing machine and with tensile coupons exhibiting gauge length of 50 mm [19]. The dynamic strain rate of 1 s^{-1} was performed with the 100 kN Electro-Servo-Hydraulic Universal test machine, while the dynamic strain rates of 100 and 200 s^{-1} were performed with the 100 kN Servo-Hydraulic High Rate Impact test machine (where all tensile coupons subjected to dynamic strain rates exhibited gauge length of 16 mm) [12].

The raw force-displacement data resulting from tensile testing were converted to true stress-true plastic strain [12]. During this process, the dynamic tensile data were ‘smoothed’ with a polynomial trendline in order to eliminate noise resulting from shockwaves that are transmitted from the testing machine to the specimen under dynamic strain rate conditions [12].

The true stress-true plastic strain data resulting from the conversion process are only valid during uniform elongation and to the commencement of ‘necking’. Thus, the true stress-true plastic strain data had to be extrapolated over the full true plastic strain range. This was achieved with the ‘half linear-log linear’ extrapolation method (Equation 1) [20]. The half linear-log linear extrapolation method is accepted throughout Tata Steel and is routinely employed to produce the ‘FE Curve’ for finite element simulations. Critical tensile properties were derived from this final true stress-true plastic strain curve (Fig. 1).

In addition to the common tensile properties, including (true) proof strength, (true) ultimate tensile strength, uniform (plastic) elongation and total (plastic) elongation, modulus of toughness (from here on referred to as just ‘toughness’) was also derived. Toughness is a measure of energy absorption per unit volume and can be derived from the area under the stress-strain curve. Two toughness values were determined: 1) toughness (2 % plastic strain); and 2) toughness (total plastic strain). Toughness (total plastic strain) was derived from the area under the entire true stress-true plastic strain curve. Toughness (2 % plastic strain) was derived from the area under the true stress-true plastic strain curve up to a fixed true plastic strain value of 2 %. It is beneficial to evaluate toughness up to a limited and fixed strain value in this manner since automotive structural body components are rarely strained to fracture in a crash event, therefore applying a limited strain value to the toughness evaluation is perhaps more realistic [16].

$$\sigma = 0.5\left\{\left[\sigma_u + k\left(\varepsilon - \varepsilon_g\right)\right] + \left[\sigma_u\left(\frac{\varepsilon}{\varepsilon_g}\right)^n\right]\right\} \tag{1}$$

Where: σ = stress (MPa)
σ_u = stress at necking (MPa)
k = work hardening rate (MPa)
ε = strain
ε_g = strain at necking
n = work hardening exponent

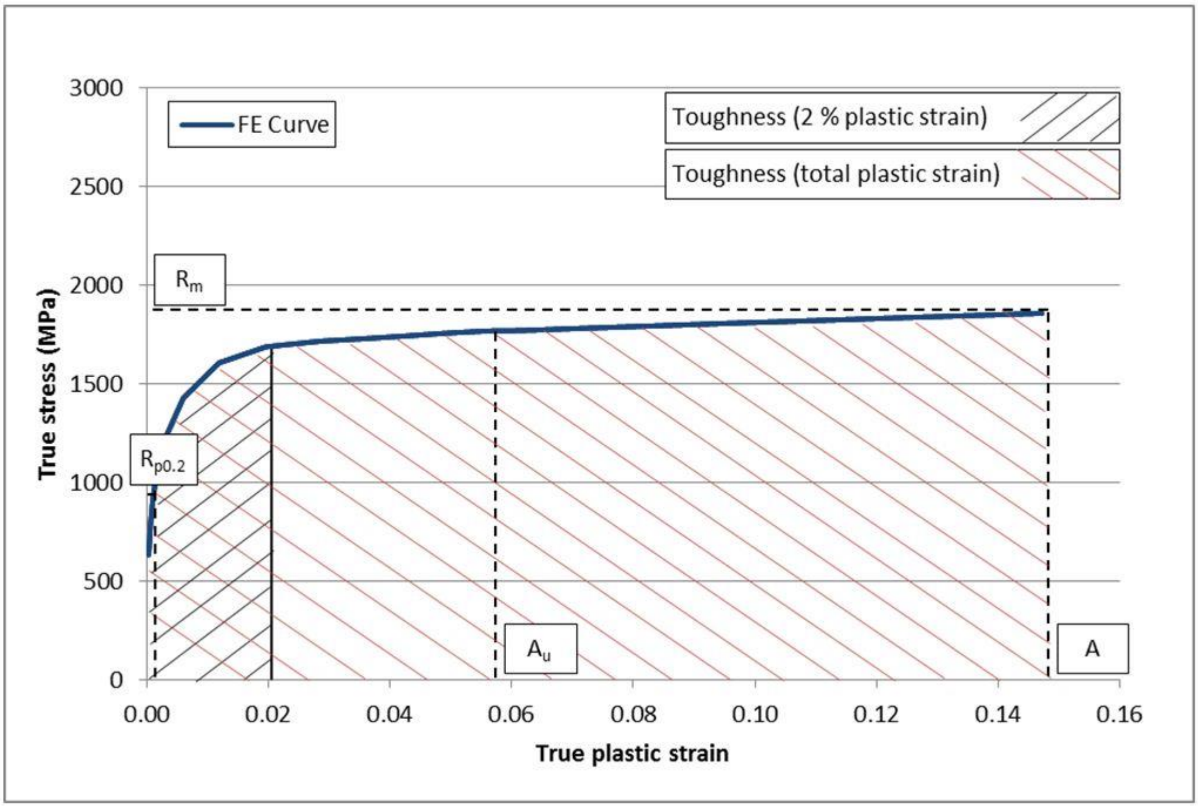


Fig. 1: True stress-true plastic strain curve

3 Results & Discussion

Figs. 2a-f present tensile properties [(true) proof strength-$R_{p0.2}$, (true) ultimate tensile strength-R_m, uniform (plastic) elongation-A_u, total (plastic) elongation-A, toughness (2 % plastic strain) and toughness (total plastic strain)].

For 22MnB5, increasing strain rate from 0.001 to 1 s^{-1} resulted in increasing proof strength and ultimate tensile strength, but decreasing uniform elongation and total elongation. Conversely, increasing strain rate from 1 to 100 and to 200 s^{-1} resulted in generally decreasing proof strength and ultimate tensile strength, but generally increasing uniform elongation and total elongation. The contradictory response between tensile strength and elongation (particularly proof strength and uniform elongation) to increasing strain rate resulted in similar toughness (2 % plastic strain) across all four strain rates. However, increasing elongation (particularly total elongation) with increasing strain rate from 1 to 100 and to 200 s^{-1} resulted in significantly higher toughness (total plastic strain). These observations illustrate the strong influence of proof strength on toughness (2 % plastic strain) and moreover, the very strong influence of total elongation on toughness (total plastic strain). The latter is clearly evident from the manner in which the ‘total elongation’ chart is almost an exact replica (depicts exactly the same trends) of the ‘toughness (total plastic strain)’ chart.

For 15MnCr5, increasing strain rate from 0.001 to 1 s^{-1} resulted in increasing proof strength, but decreasing total elongation. Conversely, increasing strain rate from 1 to 100 and to 200 s^{-1} resulted in consistently decreasing proof strength, but consistently increasing total elongation. Ultimate tensile strength and uniform elongation demonstrated variable and anomalous responses to increasing strain rate. The very strong influence of total elongation on toughness (total plastic strain) is again apparent.

For 25MnVB5, increasing strain rate from 0.001 to 1 s^{-1} resulted in increasing proof strength. Conversely, increasing strain rate from 1 to 100 and to 200 s^{-1} resulted in consistently decreasing proof strength. Increasing strain rate across all four strain rates resulted in generally increasing ultimate tensile strength, uniform elongation and total elongation. Consequently, increasing strain rate across all four strain rates resulted in consistently increasing toughness (2 % plastic strain) and particularly, consistently increasing toughness (total plastic strain).

For 38MnB5, increasing strain rate across all four strain rates resulted in generally increasing proof strength and consistently increasing ultimate tensile strength. Increasing strain rate from 0.001 to 1 s^{-1} resulted in decreasing uniform elongation and total elongation. Conversely, increasing strain rate from 1 to 100 and to 200 s^{-1} resulted in generally increasing uniform elongation and total elongation. Consequently, the highest strain rates of 100 and 200 s^{-1} resulted in significantly higher toughness (total plastic strain).

Strain rate sensitivity (m-value) is defined as the variation of tensile strength (usually proof strength) with increasing strain rate and is expressed as the gradient of the log strain rate-log tensile strength plot [13]. Given that four strain rates were investigated, three m-values were calculated, in addition to the mean m-value across all four strain rates (Table 2). Each steel demonstrated positive strain rate sensitivity (increasing proof strength) with increasing strain rate from 0.001 to 1 s^{-1}. However, each steel demonstrated negative strain rate sensitivity (decreasing proof strength) with increasing strain rate from 1 to 100 s^{-1}. Moreover, 15MnCr5 and 25MnVB5 also demonstrated negative strain rate sensitivity with increasing strain rate from 100 to 200 s^{-1}.

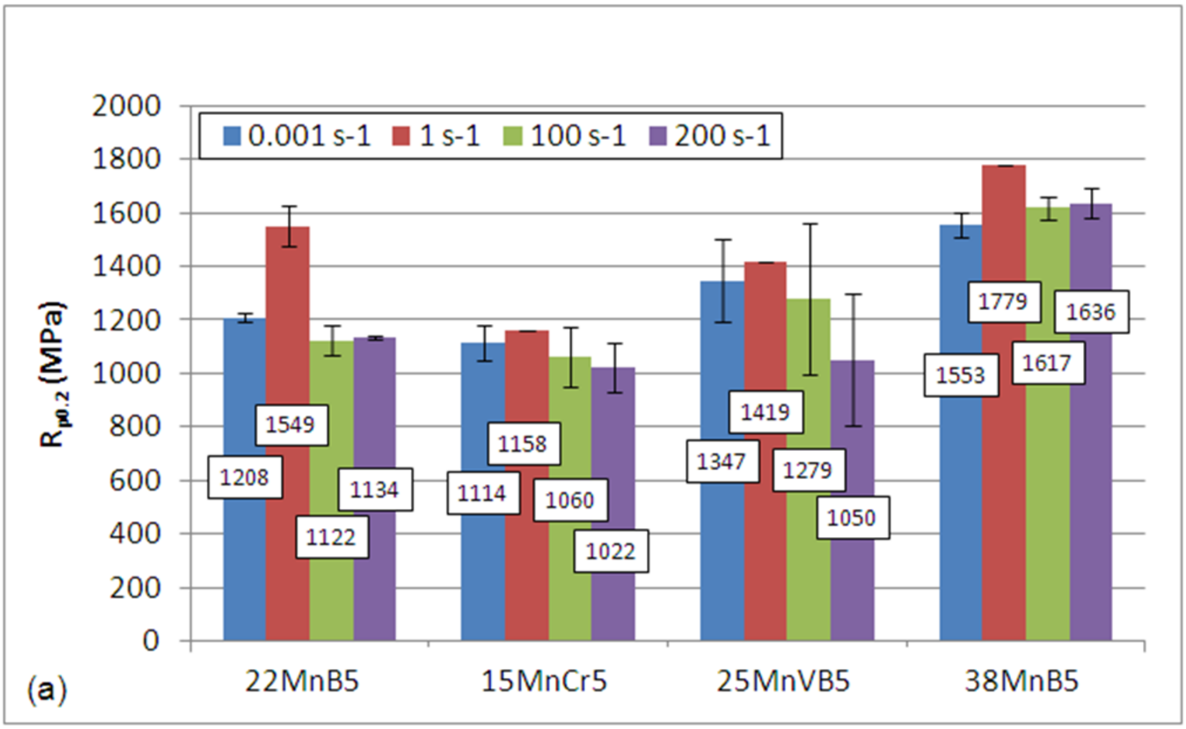
Positive strain rate sensitivity with increasing strain rate from 0.001 to 1 s^{-1} can be attributed to the breakdown of dislocation cell structures. It has been reported [13] that under low strain rates, plastic deformation takes place with dislocations forming ordered dislocation cell structures. However, under high strain rates, dislocation cell structures demonstrate a tendency to breakdown, leading to more dislocation nucleation sites for the subsequent generation of dislocations within the plastic deformation process. Thus, the final dislocation density is relatively large. The increase in dislocation density then gives rise to strengthening through work hardening. This characteristic of dislocation cell structures forming and being maintained under low strain rates, but dislocation cell structures breaking down under high strain rates, has been reported [13] [16] [17] to be particularly common in mild carbon ferritic steels, such as CMn and HSLA steels, giving rise to relatively high strain rate sensitivity values of typically 0.07. However, in multiphase steels such as DP and TRIP steels, it has been reported [13] [16] that dislocation cell structures are inhibited from forming regardless of the strain rate, due to interactions between dislocations and hard secondary phases or precipitates. It is for this reason that DP and TRIP steels have been reported [13] [16] to demonstrate lower strain rate sensitivity values than ferritic steels, typically in the order of 0.02-0.03. It is proposed that here for the hot stamped martensitic steels, greater breakdown of dislocation cell structures and thus, higher dislocation density under higher strain rates was a factor, leading to positive strain rate sensitivity with increasing strain rate from 0.001 to 1 s^{-1}. However, the magnitude of greater dislocation cell structure breakdown with increasing strain rate was relatively small, with dislocation cell structures inhibited from forming (to some extent) regardless of the strain rate, due to interactions between dislocations and the numerous boundaries found in lath martensite, namely packet, block and lath boundaries.

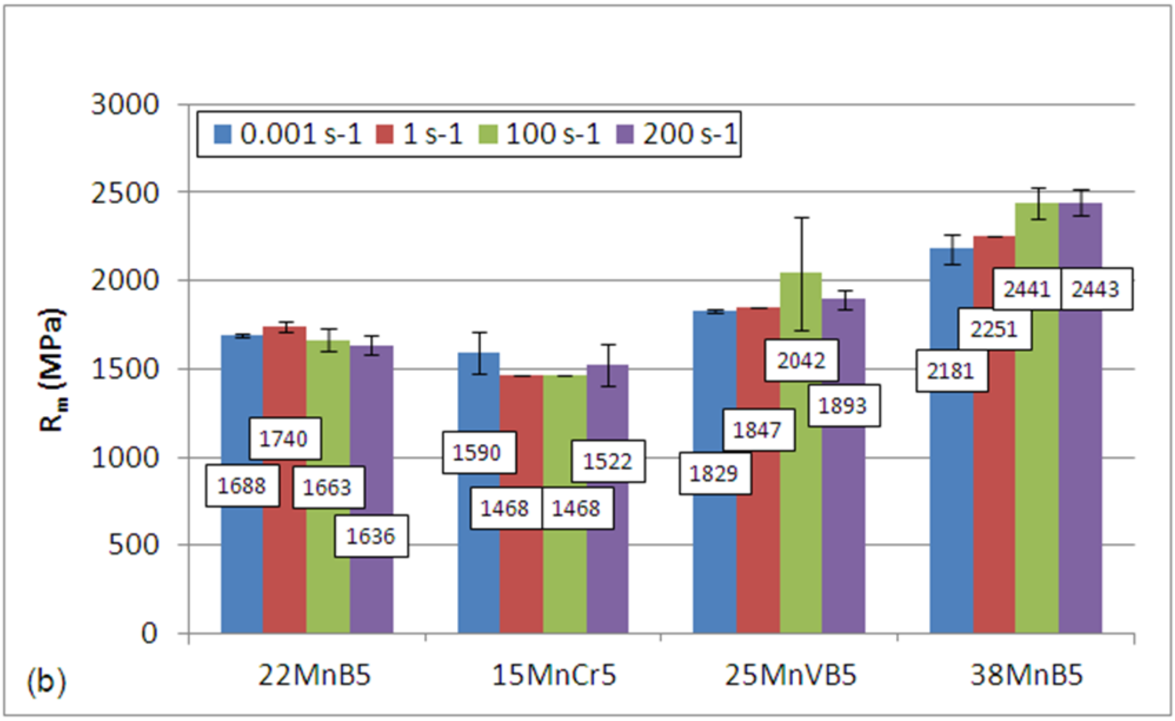
Negative strain rate sensitivity with increasing strain rate from 1 to 100 and to 200 s^{-1} can be attributed to adiabatic heating [13] [21]. During plastic deformation, a portion of mechanical energy is transferred to heat energy. It has been reported [13] [21] that under low strain rates, the heat energy generated has opportunity to dissipate from the deformed region to the external atmosphere. However, under high strain rates, the heat energy does not have opportunity to dissipate rapidly enough. Thus, the heat energy remains concentrated in the deformed region throughout the plastic deformation process, leading to ‘adiabatic heating’ and in turn, weakening of inter atomic bonds. It has been reported [13] [21] that the weakening of inter atomic bonds resulting from adiabatic heating can be responsible for negative strain rate sensitivity. Here for the hot stamped martensitic steels, it is proposed that with increasing strain rate, adiabatic heating became a larger factor. Moreover, at the higher strain rates of 100 and 200 s^{-1}, softening from adiabatic heating was a more significant factor than hardening from dislocation density increase. It is for this reason that the hot stamped martensitic steels exhibited relatively low (even negative) mean strain rate sensitivity values, with the highest mean strain rate sensitivity value of 0.012 provided by 38MnB5. This compares to strain rate sensitivity values of 0.07 reported [13] [16] [17] for ferritic steels and 0.02-0.03 reported [13] [16] for DP and TRIP steels.

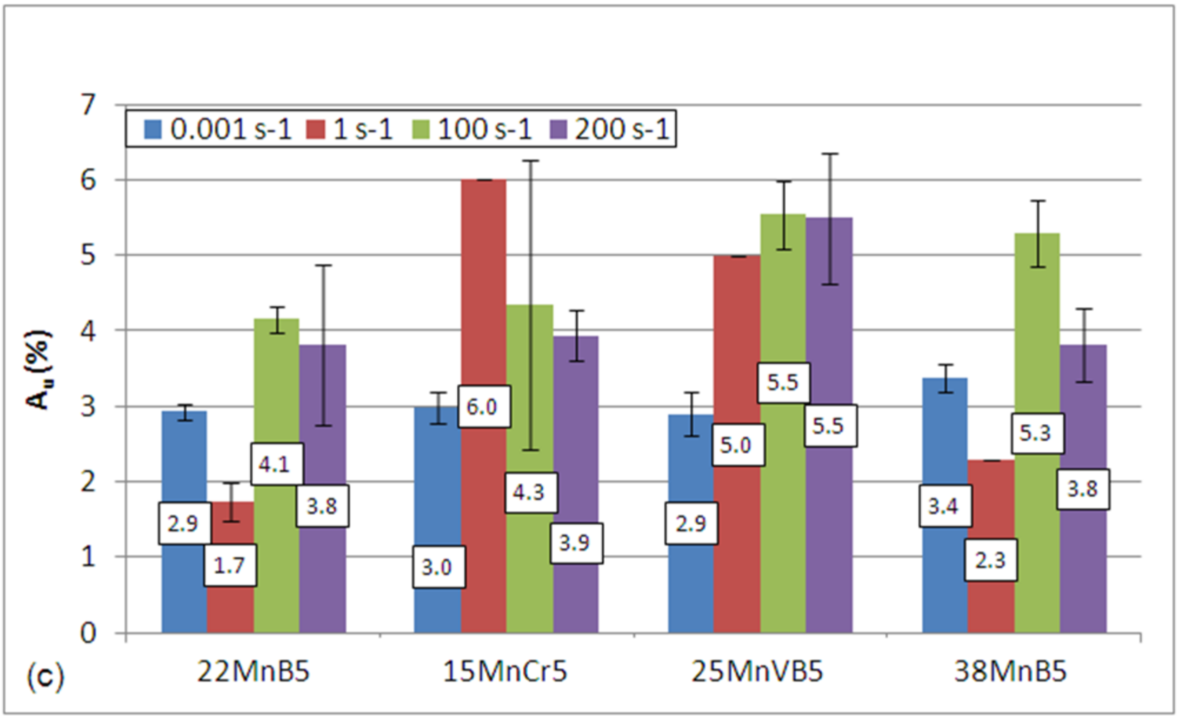
With the exception of 15MnCr5, each steel demonstrated maximum uniform elongation and total elongation given the higher strain rates of 100 and 200 s^{-1}. The adiabatic heating theory at higher strain rates may also explain this trend, where it has been reported [22] that DP and TRIP steels exhibit higher elongation values under dynamic strain rates compared to under quasi static strain rates.

38MnB5 was the only steel to demonstrate positive mean strain rate sensitivity across all four strain rates and moreover, the only steel to demonstrate consistently increasing ultimate tensile strength across all four strain rates. Further, 38MnB5 demonstrated a relatively large increase to total elongation at the higher strain rates of 100 and 200 s^{-1}. For example, the difference between the minimum and maximum total elongation of 22MnB5 was 2.7 %, whereas the difference between the minimum and maximum total elongation of 38MnB5 was 8.1 %. The relatively large increase to total elongation at the higher strain rates demonstrated by 38MnB5 may be attributed to the higher carbon content and in turn, greater rise of adiabatic heating. The proposed theory being that a greater concentration of interstitial solute carbon atoms are present to interact and generate heat, where it is known that the interstitial solute carbon atoms exhibit mobility during deformation (such as the concept of dynamic strain aging) and where the movement of atoms is known to generate heat (such as the concept of latent heat of phase transformation).

The response of 38MnB5 to increasing strain rate gave rise to significantly higher toughness compared to 22MnB5 at the higher strain rates. Moreover, by making comparison to results presented by other researchers [13] (Fig. 3), each of the hot stamped martensitic steels demonstrated higher toughness (2 % plastic strain) under the lowest strain rate of 0.001 s^{-1} than a selection of as delivered automotive steels, including XF 450 (HSLA), CMn 800, DP 600, DP 800, DP 1400, TRIP 600, TRIP 800, TRIP 950 and TRIP 1000. Under the highest strain rate of 200 s^{-1}, only as delivered DP 1400 competes with the toughness (2 % plastic strain) of the hot stamped martensitic steels.




3000
2500
2000
1500
1000
500
0
R_m (MPa)
0.001 s-1
1 s-1
100 s-1
200 s-1
1688
1740
1663
1636
1590
1468
1468
1522
1829
1847
2042
1893
2181
2251
2441
2443
22MnB5
15MnCr5
25MnVB5
38MnB5
(b)


7
6
5
4
3
2
1
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A_u (%)
0.001 s-1
1 s-1
100 s-1
200 s-1
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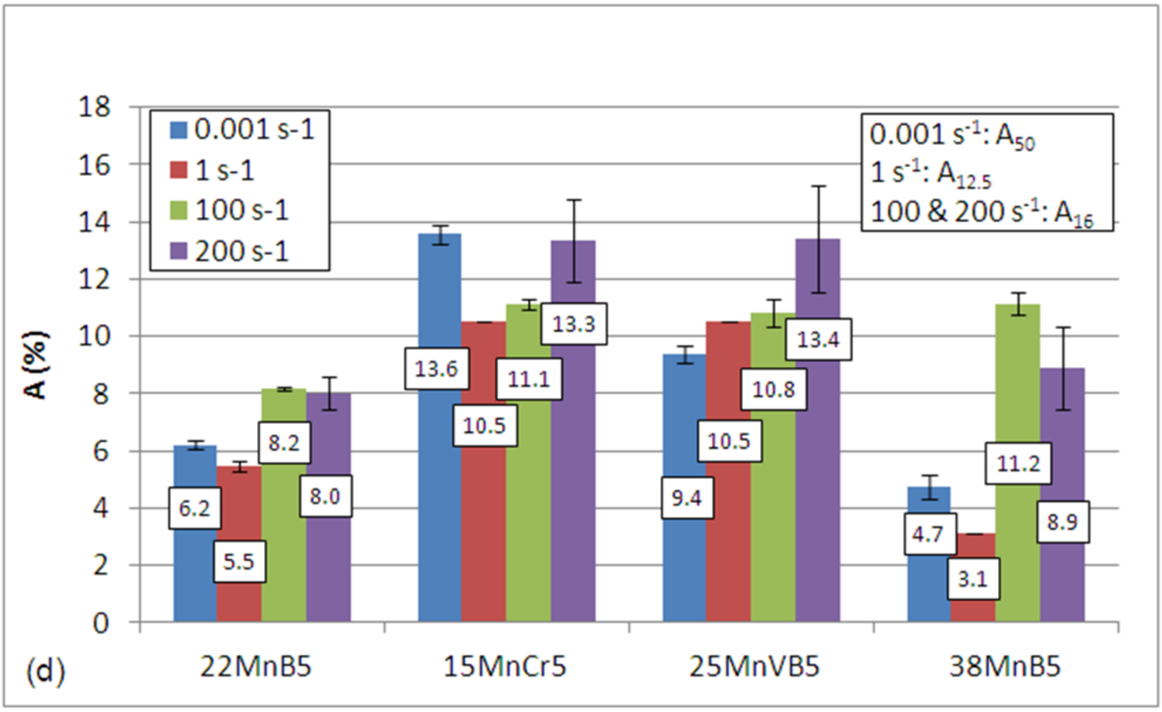
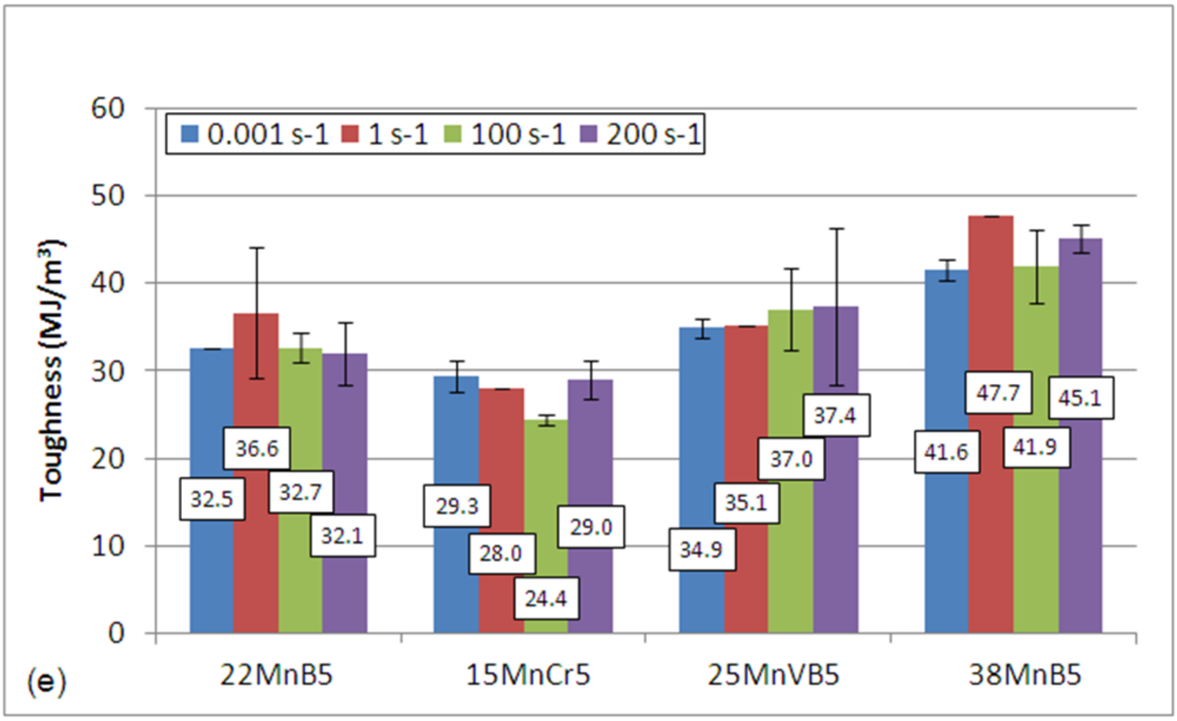
1.7
4.1
3.8
3.0
6.0
4.3
3.9
2.9
5.0
5.5
5.5
3.4
2.3
5.3
3.8
22MnB5
15MnCr5
25MnVB5
38MnB5
(c)


A (%)
0
2
4
6
8
10
12
14
16
18
🟦 0.001 s-1
🟥 1 s-1
🟩 100 s-1
🟪 200 s-1
0.001 s-1: A50
1 s-1: A12.5
100 & 200 s-1: A16
6.2
5.5
8.2
8.0
13.6
10.5
11.1
13.3
9.4
10.5
10.8
13.4
4.7
3.1
11.2
8.9
22MnB5
15MnCr5
25MnVB5
38MnB5
(d)


Toughness (MJ/m3)
0
10
20
30
40
50
60
🟦 0.001 s-1
🟥 1 s-1
🟩 100 s-1
🟪 200 s-1
32.5
36.6
32.7
32.1
29.3
28.0
24.4
29.0
34.9
35.1
37.0
37.4
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47.7
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22MnB5
15MnCr5
25MnVB5
38MnB5
(e)

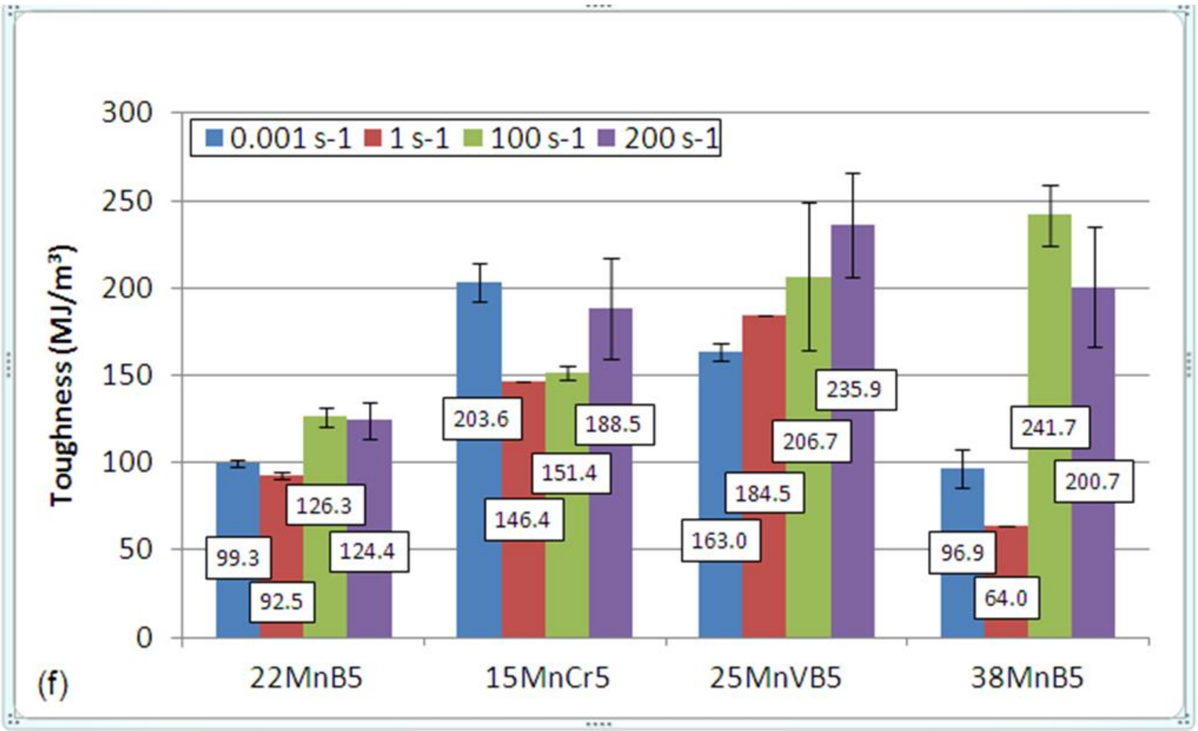

Fig. 2: Tensile properties (a) proof strength (b) ultimate tensile strength (c) uniform elongation (d) total elongation (e) toughness (2 % plastic strain) (f) toughness (total plastic strain)

Table 2: Strain rate sensitivity

	$m_{0.001\text{-}1}$	$m_{1\text{-}100}$	$m_{100\text{-}200}$	m_{mean}
22MnB5	0.083	-0.161	0.033	-0.015
15MnCr5	0.013	-0.044	-0.121	-0.051
25MnVB5	0.017	-0.052	-0.658	-0.231
38MnB5	0.045	-0.048	0.037	0.012

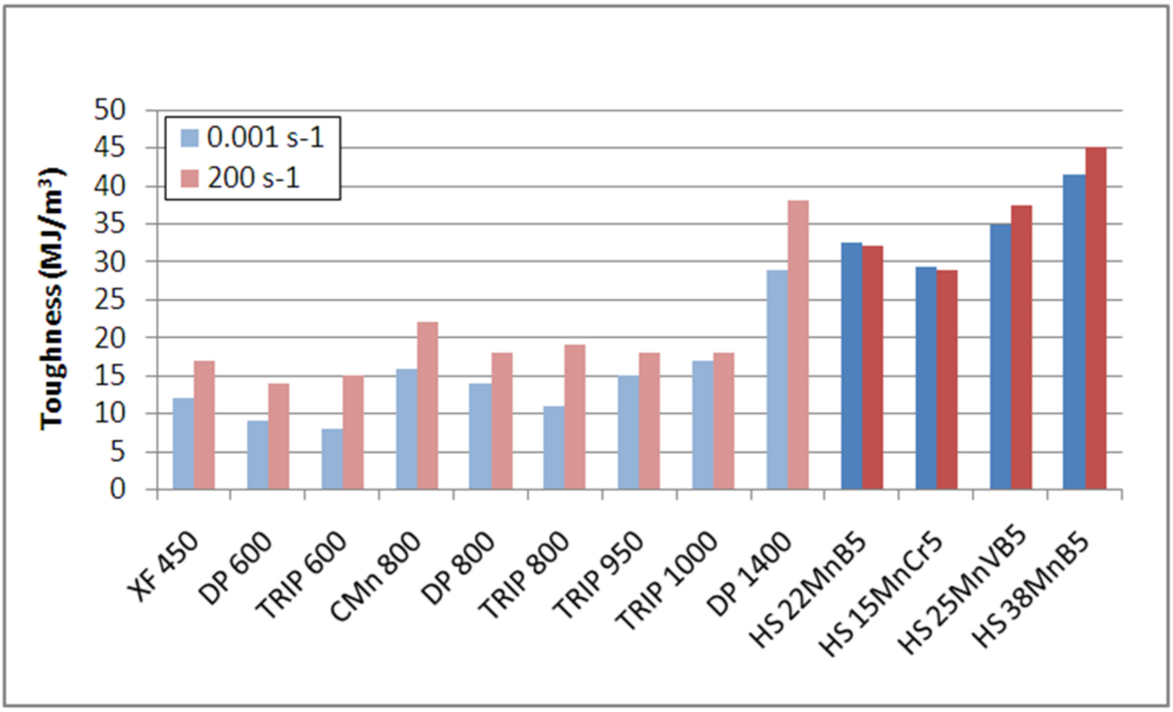

Fig. 3: Comparison of toughness (2 % plastic strain) against a selection of as delivered automotive steels

4 Conclusions

Tensile testing over strain rates of 0.001, 1, 100 and 200 s^{-1} was performed on three novel ultrahigh strength hot stamped martensitic steels, namely 38MnB5, 15MnCr5 and 25MnVB5, in addition to the 22MnB5 control steel. Each steel generally demonstrated positive strain rate sensitivity with increasing strain rate from 0.001 to 1 s^{-1} (attributed to dislocation density increase), but negative strain rate sensitivity with increasing strain rate from 1 to 200 s^{-1} (attributed to adiabatic heating). The notable exception to the above was 38MnB5, which demonstrated consistently increasing ultimate tensile strength across all four strain rates. Moreover, each steel generally demonstrated maximum elongation at strain rates of 100 or 200 s^{-1} (also attributed to adiabatic heating). The response of 38MnB5 to increasing strain rate gave rise to significantly higher energy absorption compared to 22MnB5 at the higher strain rates. It can be concluded that 38MnB5 should provide superior anti intrusive crash performance under low speed impact owing to significantly higher tensile strength under all strain rates, yet superior impact energy absorptive crash performance under high speed impact owing to significantly higher tensile strength, elongation and ultimately, energy absorption under the higher strain rates.

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