The relationships between tensile properties and hole expansion property of C-Mn steels

X. FANG, Z. FAN*, B. RALPH
Brunel Centre for Advanced Solidification Technology, Brunel University, Uxbridge, Middlesex, UB8 3PH, UK
E-mail: mtstzzf@brunel.ac.uk

P. EVANS
Corus R, D&T, Welsh Technology Centre, Port Talbot, West Glamorgan, SA13 2NG, UK

R. UNDERHILL
Product Market Development, Corus Light Strip Products, Llanwern, PO Box 10, Newport, South Wales, P19 4XN, UK

In order to investigate the effects of the microstructure and chemical compositions on the hole expansion property of C-Mn steels, four C-Mn steels were used and heat treated into different structures. The influences of the tensile properties on the hole expansion property were also investigated. It has been found in this paper that C-Mn steels with a high ratio of yield strength to ultimate tensile strength usually have a good hole expansion property. A high silicon content in solid solution can improve the hole expansion property. Carbon has a significant detrimental effect on the hole expansion property. © *2003 Kluwer Academic Publishers*

1. Introduction

The hole expansion property is also called "stretch-flangeability" [1]. There are two main kinds of hole expansion tests to determine the hole expansion property. One is used according to a Japanese standard [2], and the other is employed by Corus [3]. C-Mn steel sheets are widely used in the automotive industry. Some parts are connected or positioned by bolts through holes. When the holes are expanded steels have a tendency to split. The hole expansion property is devised to measure the percentage of the size of an expanded hole at the moment that a crack occurs. It is one of most important properties to describe the formability of steels, especially in the automotive industry. It has been found that chemical composition and microstructure, particularly the type of second phase, strongly influence the hole expansion property. For example, the hole expansion property was improved effectively in a 0.05C-0.49Si-1.6Mn steel by decreasing the sulphur content or controlling the inclusion type by adding rare earth elements or Ca [4]. The hole expansion property was improved remarkably when the pearlite in a HSLA steel or martensite in a dual phase steel was replaced by bainite [4]. Therefore, more and more steels composed of ferrite and bainite are used in the automotive industry [5]. However, most investigators have used the Japanese standard and data on the hole expansion property using the Corus standard is scarce, although the Corus standard of the hole expansion is widely used in

the automotive industry particularly in Europe. Thus, in this paper, the relationships between the microstructure, composition, tensile properties and the hole expansion property using the Corus standard are investigated.

2. Experimental procedures

Table I shows that the chemical compositions of four steel sheet grades used in this study and their thickness gauges were 2.63 mm, 2.55 mm, 2.16 mm and 2.62 mm, respectively. In carbon manganese steels, the strengthening mechanism is based on the presence of a controlled volume fraction of a hard second microstructural micro-constituent in a fine ferrite matrix. A fine ferrite grain size is achieved by finishing the hot rolling just above the Ar_3 temperature (860–870°C) and cooling rapidly to the temperature region where the kinetics for ferrite formation is rapid, typically 600 to 700°C. Pearlite and bainite are generated by rapid cooling to coiling temperatures of 600–650°C and 350–400°C, respectively. The hot rolling temperature of steel H1 was about 860°C and it was then quickly cooled to about 720°C. The coiling temperature was about 650°C to generate pearlite. The hot rolling temperature of steels H2, H3 and H4 was about 860°C and they were then quickly cooled to about 720°C. In order to generate bainite, a coiling temperature of about 450°C was used.

The as-hot-rolled steel sheets were cut along the rolling direction to produce flat test pieces 25 mm in

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TABLE I Chemical composition (in wt%) of the steels used in this project

Steel	C	Si	Mn	S	P	Al (Tot.)	N	Fe
H1	0.130	0.073	0.85	0.004	0.032	0.030	0.0038	Bal.
H2	0.120	0.044	1.34	0.001	0.021	0.033	0.0030	Bal.
H3	0.100	0.790	1.20	0.001	0.013	0.043	0.003	Bal.
H4	0.312	0.270	1.51	0.008	0.021	0.029	0.0031	Bal.

width and 180 mm in length for 50 mm gauge length tensile samples, and into 100 mm squares for the hole expansion samples. These samples were cut from different positions across the width of the sheet. A schematic illustration of the heat treatment cycles used in present study is shown in Fig. 1. This figure will be used to facilitate the description of the heat treatment procedures for the creation of different microstructures. All samples were cold-rolled down to 1.0 mm in thickness and cut to the size of a tensile test sample of 10 mm gauge length with the long sides parallel to the rolling direction for tensile tests and 100 mm squares for the hole expansion tests before heat treatment. The heat treatment process in a fluidized bath and a muffle furnace was to heat and hold samples at 900°C for 180 s in a muffle furnace and then quench to the fluidized bath at different quenching temperatures. However, the samples with small gauge thickness (1 mm) proved to be too thin to retain their temperature near enough to 900°C during the transfer from the muffle furnace to the fluidized bath in order to avoid decomposition of some of the austenite, accordingly a steel sample holder was constructed in order to retain the heat in the sample. Both the sample and holder were taken from the muffle furnace and separated just before the sample was quenched into the fluidized bath. With this procedure the temperature of the sample only dropped 10 to 20°C when it was removed from the muffle furnace for quenching into the fluidized bath. Samples for generating a ferrite + bainite microstructure were soaked at 900°C and held for

180 s and then were cooled to 400°C. After quenching, the samples were held for 240 s and finally cooled down to room temperature in water.

Samples for metallographic examination were cut along their rolling direction and the normal direction of the sheet surface. The sections of samples were ground, polished down to 1 μm and etched in a 2% nital solution. A JEOL JXA-840A SEM was used to investigate the microstructure of samples. Tensile testing of the as-hot-rolled samples and heat treated samples was conducted in a Zwick machine with initial strain rates of 7.4×10^{-4} s^{-1} and 3.1×10^{-4} s^{-1}, respectively. Extensometers were employed for measuring the strains in the tensile tests. In this work the hole expansion test of the Corus Standard was employed. This test was conducted on an Erichsen 60 tonne hydraulic press. A sketch of the hole expansion test is shown in Fig. 2. Before the test a 12 mm (± 0.1 mm) hole is punched in the centre of each sample. The hole expansion test is conducted by expanding the punched hole using a 50 mm diameter punch. The initial diameter d_0 of the hole of the test sample is measured by averaging two readings taken perpendicularly to each other. When a tear at the edge of the expanding hole of the test sample is observed, the travel of the punch is stopped immediately. The final diameter d_f of the hole of the test sample is measured in the same way as the initial diameter. The hole expansion value, η, is calculated using the following equation:

$$\eta = \frac{d_f - d_0}{d_0} \times 100\% \qquad (1)$$

3. Results
SEM micrographs of the as-hot-rolled steels H1, H2, H3 and H4 are shown in Fig. 3a–d, respectively. The average grain sizes of the ferrite and pearlite or bainite of samples H1, H2 and H3 are smaller than those of steel H4. Fig. 3a shows that the microstructure of
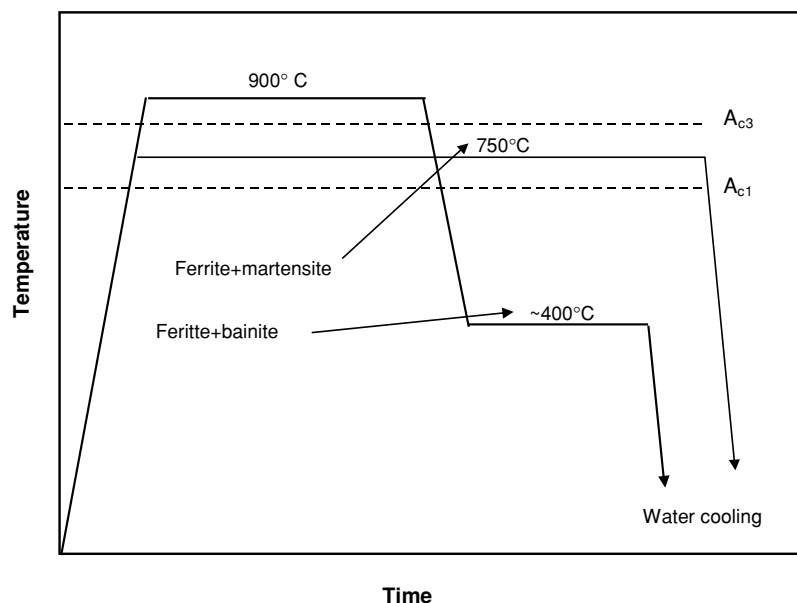

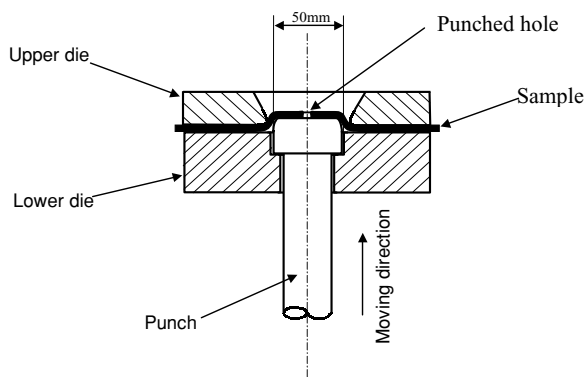Figure 1 A schematic illustration of the heat treatment schedule.

Figure 2 A schematic illustration of the hole-expansion tester.

the as-hot-rolled steel H1 consisted of polygonal ferrite and pearlite; Fig. 3b–d shows that the microstructure of the as-hot-rolled steels H2, H3 and H4 consists of polygonal ferrite and bainite. The volume factions of the second microstructural constituent (*VFS*), i.e., the pearlite in steel H1 and the bainite in steels H3, H2 and H4, were 10%, 10%, 20% and 44%, respectively (Table II).

Samples H1-B, H2-B, H3-B and H4-B were heated to 900°C and held for 180 s, and then quenched into a 400°C fluidized bath. The microstructures of samples H2-B, H3-B and H4-B were not significantly different from those of as-hot-rolled samples but the pearlite was replaced by bainite in sample H1-B compared with its as-hot-rolled sample. The volume fractions of bainite in samples H1-B, H2-B, H3-B and H4-B were 18%, 16%, 17% and 43%, respectively.

The mechanical properties of as-hot-rolled and heat-treated samples are listed in Table II. Because the conditions across the width of steel sheet were different during hot rolling, for example, the temperature at edges should be lower than that in the middle of steel sheets, the mechanical properties at different positions across
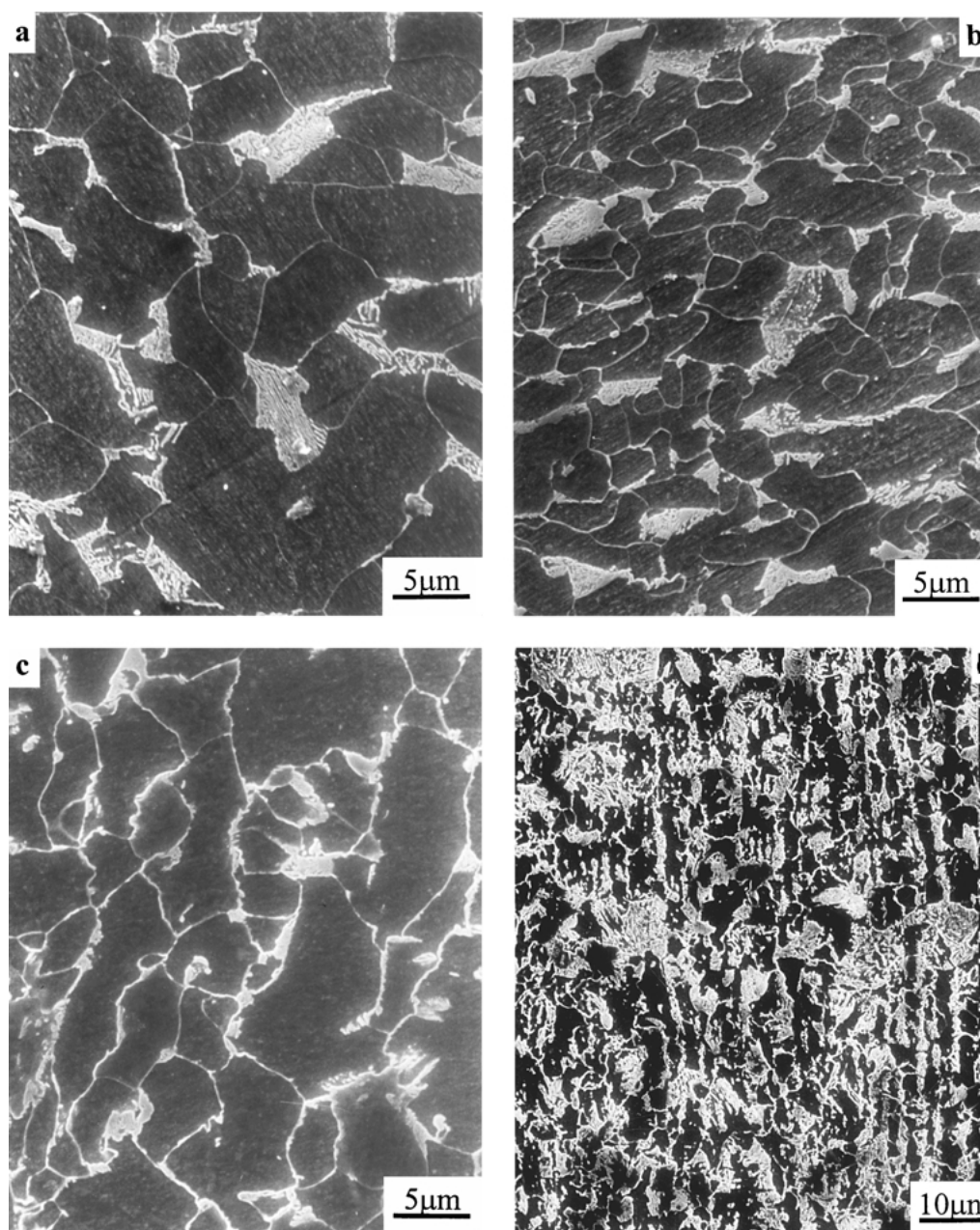

Figure 3 SEM micrographs of the as-hot-rolled steels: (a) H1, (b) H2, (a) H3, and (b) H4.

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TABLE II Mechanical properties of H1, H2, H4 and H3 with a dual-microstructure

Sample designation	σ_y (MPa)	σ_{UTS} (MPa)	σ_y/σ_{UTS} (%)	ε_u (%)	H.E. (%) (1 mm gauge)	H.E. (%) (original gauge)	VFS (%)
H1-as-hot-rolled	381.0	509.0	74.8	19.0	–	36.8	10
H2-as-hot-rolled	450.6	558.9	80.6	15.9	–	53.0	20
H3-as-hot-rolled	434.5	568.9	76.6	19.6	–	72.8	10
H4-as-hot-rolled	527.8	730.1	72.4	11.4	–	21.2	44
H1-B	404.4	502.0	85.8	20.2	50.0	56.0	18
H2-B	395.4	484.5	81.6	18.6	56.0	60.0	16
H3-B	455.4	552.5	82.4	19.1	66.8	72.8	17
H4-B	537.5	713.2	75.4	13.5	22.1	24.5	43
H1-DP	375.5	730.0	51.4	14.7	15.0	18.6	18
H2-DP	377.2	747.6	50.5	14.0	20.0	25.7	17
H3-DP	379.0	759.3	49.9	13.1	30.5	34.6	16

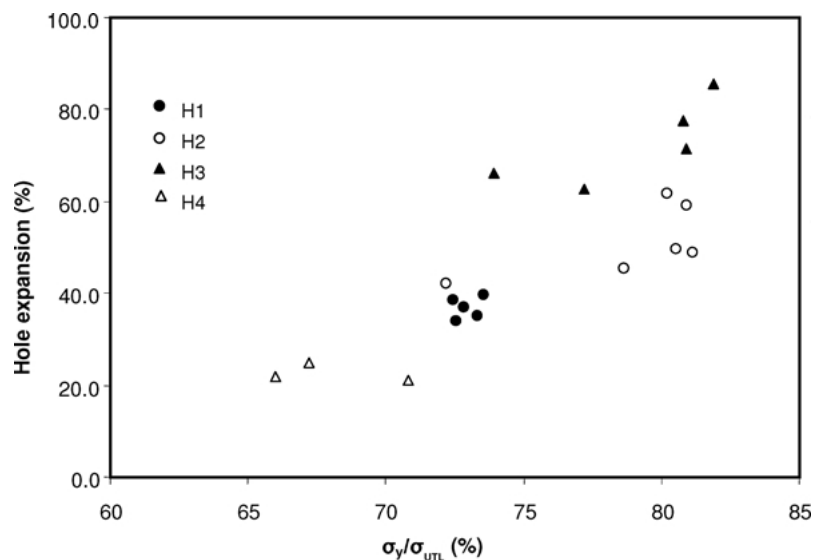*Figure 4* Effect of σ_y/σ_{UTL} ratio on the hole expansion property.

the width of sheets should be different. Therefore, the results of as-hot-rolled samples in Table II are only the averages of samples at different positions across the width of steel sheets. The tensile test properties and their hole expansions at different poisons are plotted in Fig. 4. The hole expansion properties of steels H2 and H3 steels increase with increasing the σ_y/σ_{UTL} ratio. At the same range of σ_y/σ_{UTL}, the hole expansion properties of steel H3 are superior to those of steel H2. Compared with the hole expansion properties of all four as-hot-rolled samples, it can be also seen that the hole expansion property increases with increase in the ratio (σ_y/σ_{UTL}) of yield strength to ultimate tensile strength. The hole expansion properties of samples H1-B, H2-B and H3-B also increase with increasing the σ_y/σ_{UTL} ratio. Meanwhile, the samples with a higher gauge thickness showed better hole expansion properties (Table II).

Samples H1-DP, H2-DP and H3-DP were quenched into water from the intercritical temperature of 750°C. The volume fractions of martensite in samples H1-DP, H2-DP and H3-DP were 18%, 17% and 16%, respectively. There is no significant difference of the uniform elongations and yield strength in these three samples, but their ultimate tensile strengths are quite different. The ultimate tensile strengths of dual phase samples H1-DP, H2-DP and H3-DP are 730.0 MPa, 747.6 MPa

and 759.3 MPa, respectively. Although the volume fractions of the second phase martensite of these three samples are not significantly different, their hole expansion properties are quite different. The hole expansion properties of steels H1, H2, and H3 with 1.0 mm gauge thickness are 15%, 20% and 30.4%, respectively. With a gauge thickness increase (original gauge without cold rolling) the hole expansion properties of steels H1, H2, and H3 increased to 18.6%, 25.7% and 34.6%, respectively.

4. Discussion
4.1. Effect of matrix strength on hole expansion property

Although steels H1, H2 and H3 have the same microstructure, no matter what the second constituent is, beinite or martensite, and no significant difference in the volume fraction of the second micrstructure constituent as well, their hole expansion properties are quite different. The main difference among these three steels is their compositions which result in their property differences, especially the properties of the matrix (ferrite). The properties of the matrix are hardly tested experimentally. However, they are easily calculated according to their compositions. We believe that

TABLE III Calculated yield strength and ultimate tensile strength of ferrite in steels H1, H2 and H3

Steels	Yield strength (MPa)	Ultimate ensile strength (MPa)
H1	97.5	323.8
H2	112.0	334.9
H3	203.6	414.7

the accuracy of these calculations should be enough for comparing the tensile properties of the ferrites in the above samples.

Assume that silicon, manganese and free nitrogen in the ferrite of these three steels are the same as their average concentrations and the ferrite grain sizes are all 3 μm. The yield strength and ultimate tensile strength of ferrites in these three steels can be calculated by Pickering and Gladman's empirical relationships [6]:

$$\sigma_y \text{ (MPa)} = 53.9 + 32.3\%\text{Mn} + 83.2\%\text{Si}$$
$$+ 354\text{N}_f + 17.4d^{-1/2} \quad (2)$$

$$\sigma_{UTS} \text{ (MPa)} = 294 + 27.7\%\text{Mn} + 83.2\%\text{Si}$$
$$+ 3.85\%\text{Pearlite} + 7.7d^{-1/2} \quad (3)$$

where d is the mean ferrite grain size in mm and N_f is the free (soluble) nitrogen.

The yield strengths and ultimate tensile strengths of their ferrite were calculated and are listed in Table III. The calculated ferrite yield strengths of steels H1, H2 and H3 were 97.5 MPa, 112 MPa and 203 MPa, respectively. The calculated ferrite ultimate tensile strengths of steels H1, H2 and H3 were 323.8 MPa, 334.9 MPa and 414.7 MPa, respectively. The calculated strengths of both the yield strength and ultimate tensile strength of steel H3 were much higher than those of steels H1 and H2. The strength of bainite strongly depends on the carbon concentration of steels. The differences of the carbon concentrations between steels H1, H2 and H3 are not large enough to make significant differences in the strengths of pearlite or bainite in these steels. Furthermore, although the concentrations of silicon and manganese in steels H1, H2 and H3 are different, the tensile properties of bainite in these steels mainly depend on carbon concentration. Equation 2 shows that pearlite (i.e., carbon) has little or no effect on the yield stress of low-carbon steels. Therefore, the yield strength of a low carbon steel mainly depends on the strength of the softer phase, ferrite. Thus, a high strength of the matrix will lead to a decrease in the strength differences between matrix and second microstructural constituent of C-Mn steels, which is prone to increase the σ_y/σ_{UTL} ratio. This could be the reason why steels with a high σ_y/σ_{UTL} ratio have a good hole expansion property. Thus, the matrix (ferrite) could be one of major factors affecting the hole expansion property of C-Mn steels.

Table II shows that the ferritic + martensite steel was obtained by annealing at the intercritical temperature and then quenching into the cooling media. Therefore, the chemical compositions in the ferrite of samples with a ferrite + martensite structure were close to the equilibrium concentrations. Thus, the strength differences

between the harder phase and softer phase of dual phase steels are much higher than those of samples with a structure of ferrite + pearlite or ferrite + bainite. This could be another reason why dual phase steels have a lower hole expansion property.

4.2. Effect of internal stress on hole expansion property

The magnitude of internal stress in the structure of a ferrite-martensite steel will depend on the volume fraction and nature of the second phase and on the stress relaxation during cooling. After a slower cooling, which results in the formation of pearlite or bainite, a lower residual stress can be expected compared with the martensite obtained by fast quenching. Gerbase et al. [7] attempted to quantify the initial distribution of residual stress in a very approximate manner. They showed that the value of the elastic back stress in the ferrite-martensite steel saturates after small strains of 1%. It has been found that even a very low volume fraction of martensite in dual phase steels results in a lowering of the initial flow stress. The residual stresses results in a high dislocation density surrounding the martensite islands, where it is easy to form some microcracks on the edge of the punched hole [8]. These microcraks are easily propagated during expanding. Therefore, the results in Table II show that the hole expansion values of steels H1, H2 and H3 with a ferrite + martensite structure were much lower than those with a ferrite + bainite or ferrite + pearlite structure. Recent work [9] further confirmed this point, i.e., the hole expansion property can be significantly improved by substantially reducing the internal stresses through tempering.

4.3. Effect of chemical concentration on hole expansion property

The silicon concentration in steel H3 is 0.79 wt% which is much higher than those in steels H1 and H2. No matter what kind of microstructure (containing bainite or martensite) steel H3 always has better hole expansion properties than steels H1 and H2 have if they had the same microstructure. This is because silicon in solid solution not only increases strength but its presence also has a minimal detrimental effect on ductility considering its ability to increase strength by its presence in solid solution. The use of high silicon additions generally results in better combinations of strength and formability [10, 11].

The silicon concentration in steel H4 is quite high (0.27 wt%). Meanwhile sample H4-B consisted of ferrite and bainite. According to the discussion above, the hole expansion property of sample H4-B should be better than it was. Unfortunately, this steel always showed quite low formability no matter what microstructure it had. Sugimoto et al. [8] found that a warm hole expansion property of a TRIP (transformation-induced plasticity)-aided ferrite-martensite steel can be improved by increasing the volume fraction of retained austenite and the carbon concentration in the retained austenite. The higher the volume fraction of retained austenite and higher the

carbon concentration in the retained austenite the lower the carbon concentration in the martensite. Meanwhile the formability of retained austenite has been little influenced by its carbon concentration. Therefore, according to the results in [8], it can be concluded that a high carbon concentration in a steel is harmful to its hole expansion property. Steel H4 has a much higher carbon concentration than steels H1, H2 and H3. This could be the reason why the hole expansion property of steel H4 is very low.

5. Conclusions

1. A high strength of the soft matrix in a dual-microstructure C-Mn steel increases the hole expansion property. The strength difference between harder and softer microstructures is one factor affecting the hole expansion property. The higher the difference the lower the hole expansion property.

2. Though microstructure and heat treatment conditions strongly affect the hole expansion property, carbon has a significant detrimental effect on the hole expansion property.

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