Sheared Edge Extension of High-Strength Cold-Rolled Steels

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The edge formability of a spectrum of high-strength cold-rolled steels has been evaluated using the hole expansion test. The effects of edge condition, microstructure, and tensile properties on hole expansion performance were determined. Modification of stringer inclusions through rare-earth treatments caused the hole expansion response of these steels to be much less sensitive to edge condition, as-blanked vs de-burred. Independently of edge condition, rare-earth treatment also produced a significant increase in hole expansion performance compared to the same steel untreated. Circle grid analysis showed that deformation modes generated in a hole expansion test are drawing near the hole edge, stretching farther from the edge, and plane strain separating these two modes. Recovery annealed steels with low transverse ductility were observed to fail away from the edge in the plane strain region during hole expansion. The hole expansion performance of the entire range of steels tested was found to vary linearly with the product of the steels' transverse total elongation and r_m *values. A phenomenological expression that determines hole expansion performance was derived using linear analysis. It predicts that for steels with total elongations of about 30 pct, each increase in* r_m *of about 0.1 will increase its hole expansion performance by greater than 10 pct.*

INTRODUCTION

A problem of great concern in sheet metal forming is the extension of sheared edges, either at the outside edge of a blank, or along an internal-punched hole. The Hutchinson bend test,[1] the notched tensile test,[2,3,4] the stretch bend test,[5] and the hole expansion test[3,6–11] have all been utilized to assess edge formability. However, the hole expansion test has been shown to be the most sensitive of these various tests for defining the role of inclusions on edge formability.[3,6,7] The hole expansion test has been shown to provide a reproducible and accurate quantitative assessment of the edge formability of sheet steels.[8]

Blanking produces edges that contain a thin layer of metal that is highly deformed. These edges are prone to crack propagation originating at stringer inclusions, particularly MnS.[8] The hole expansion test is extremely sensitive to the degree of inclusion shape control employed in hot-rolled steels.[3,6,12] Other work has also shown that sulfide modifications can affect the edge formability of cold-rolled steels, where inclusions are broken up during cold reduction.[7,8,11] When there is sufficient inclusion shape control to avoid premature failure, the percentage hole expansion for hot-rolled steels has been found to correlate with the average plastic anisotropy, r_m.[13] A similar correlation has been observed for cold-rolled tin-plate steels.[10] For certain steels, the condition of the sheared edge can also greatly influence the extent of hole expansion.[6,8,11] Specimen thickness is another variable that can affect a steel's capacity to undergo hole expansion.[6]

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This program was designed to investigate the effects of edge condition, microstructure, and tensile properties on the edge formability of a range of high-strength cold-rolled steels. Steels, as-blanked with optimum die clearance and with the shear burr removed, were evaluated using the hole expansion test. Microstructural features examined included variations in inclusion shape through rare-earth treatments and fully recrystallized *vs* recovered ferrite matrixes. Yield strengths varied from 240 MPa (35 ksi) to 550 MPa (80 ksi) and r_m values from 0.62 to 1.08. The nature of the failure of each steel sheet was assessed. This information was used in conjunction with a linear regression analysis to determine quantitatively the correlation between tensile properties and the hole expansion response of the entire range of steels.

EXPERIMENTAL MATERIALS AND PROCEDURES

Materials evaluated in this program were comprised of commercially produced high-strength steels with gauges ranging from 0.71 to 1.45 mm. Six of the steels were fully recrystallized HSLA and the remaining two were recovery annealed (RA). Their chemistries and inclusion treatments are presented in Table I. Table II lists their mechanical properties determined by conventional tensile testing. The r-values were computed from direct measurements of the changes in width and thickness of the specimen determined at their maximum uniform elongation. The errors in the r-value measurements amounted to about ±5 pct for the HSLA steels and ±10 pct for the RA steels.

The hole expansion test was conducted by enlarging a 25 mm diameter hole with a 102 mm hemispherical punch. A schematic of the unit is shown in Figure 1. Punch and die sets were manufactured to control the burr height formed during the punching operation to a uniform height on all materials. A punch to die gap of 0.15 mm was employed. This resulted in die clearances ranging from 10 to 20 pct of the sheet thickness. Work with similar cold-rolled steels by Davies[11] has shown that hole expansion performance is independent of the die clearances used in punching the hole for clearances from 2 to 20 pct of the sheet thickness. Analysis by Weaver and Weinmann[14,15] on hot-rolled steels with a greater thickness of 6.4 mm indicates that a shear gap of 12 pct of the plate thickness produces a minimum tendency for edge cracking during subsequent bending operations. Materials were tested in the as-blanked and with-the-burr-removed conditions. The percentage hole expansion was calculated using the standard expression:[6]

$$\text{Hole Expansion (pct)} = \frac{D_f - D_0}{D_0} \times 100 \qquad [1]$$

where D_0 was the initial hole diameter and D_f, the final hole diameter. All tests were performed using a Baldwin hydraulic testing machine with a 25-ton hold-down load on each test blank to minimize metal slippage in from the flange. The 102 mm hemispherical punch was driven through the hole at a rate of approximately 50 mm/min until approaching the maximum forming load, where the rate was reduced to below 25 mm/min to aid in stopping the punch quickly at test termination. Test blanks were positioned in the forming unit such that the burr did not face the punch, and was free to extend in tension. Testing was terminated at the first visible sign of crack initiation. Some of the test samples were electrochemically etched with 2.5 mm diameter circles prior to testing in order to determine the local strain distribution about the expanding hole.

Detailed evaluations of crack initiation sites were conducted using scanning electron microscopy (SEM) in conjunction with energy and wavelength dispersive spectroscopies (EDS and WDS). These techniques, combined with optical microscopy, were used to define the general disposition of the inclusions in each of the materials.

RESULTS AND DISCUSSION

Hole Expansion Performance

The average values of three hole expansion tests run on each of the materials evaluated are presented in Table III. The

Table I. Chemical Compositions of Steels Analyzed

Material	C	Mn	P	S	Si	V	Al	Cb	Ce	La	N	O
HSLA 35	0.039	0.37	0.034	0.015	0.015	<0.01	0.063	0.023	<0.01	<0.001	0.006	0.004
HSLA 45[1]	0.076	0.68	<0.008	0.015	0.016	<0.01	0.027	0.120	<0.01	<0.001	0.008	0.004
HSLA 50	0.080	0.82	<0.008	0.012	0.021	<0.01	0.054	0.053	<0.01	<0.001	0.009	0.003
HSLA 50[2]	0.094	0.50	<0.008	0.012	0.018	<0.01	0.033	0.041	0.02	0.004	0.008	0.005
HSLA 60[2]	0.070	1.45	0.008	0.009	0.30	0.06	0.044	0.100	0.02	0.001	0.011	0.001
RA 70	0.046	0.39	<0.008	0.016	<0.01	<0.01	<0.01	<0.01	<0.01	<0.001	0.002	0.021
RA 80	0.068	0.44	0.012	0.022	<0.01	<0.01	<0.01	<0.01	<0.01	<0.001	0.002	0.039

[1] Galvanized

[2] Rare-earth treated

Table II. Mechanical Properties of Steels Analyzed

Material	Gauge (mm)	Direction	Yield Strength (MPa)	Yield Strength (ksi)	Tensile Strength (MPa)	Tensile Strength (ksi)	Elongation (Pct) Total	Elongation (Pct) Uniform	r	r_m
HSLA 35	1.12	L	247	35.8	385	55.9	34.8	22.3	0.80	1.08
		D	252	36.6	379	54.9	35.5	24.0	1.18	
		T	262	38.0	391	56.7	36.7	23.4	1.15	
HSLA 45	0.71	L	339	49.2	421	61.0	27.5	19.8	0.67	0.88
		D	348	50.5	406	58.9	29.6	20.0	1.05	
		T	370	53.6	414	60.1	22.8	17.0	0.76	
HSLA 50	0.79	L	386	56.0	492	71.4	25.7	21.4	0.67	0.97
		D	390	56.6	483	70.0	28.4	21.8	1.12	
		T	407	59.1	501	72.7	24.4	19.5	0.95	
HSLA 50[1]	0.79	L	399	57.8	462	67.0	29.6	20.5	0.66	0.99
		D	403	58.4	463	67.1	26.0	18.5	1.16	
		T	423	61.4	478	69.3	26.2	20.0	0.99	
HSLA 50[1,2]	0.79	L	359	52.1	439	63.7	31.7	18.5	0.54	0.96
		D	379	54.9	448	65.0	39.6	25.0	1.05	
		T	390	56.5	453	65.7	30.6	18.0	1.18	
HSLA 60[2]	1.45	L	453	65.7	561	81.4	23.2	16.8	0.48	0.96
		D	456	66.1	531	77.0	27.3	18.5	1.39	
		T	503	73.0	584	84.7	22.6	16.2	0.59	
RA 70	1.27	L	468	67.9	508	73.7	14.4	5.5	0.56	0.69
		D	499	72.4	531	77.0	9.9	5.2	0.75	
		T	517	75.0	545	79.1	8.3	5.2	0.71	
RA 80	1.07	L	511	74.1	556	80.6	14.8	9.3	0.54	0.62
		D	537	77.9	571	82.8	11.8	7.8	0.68	
		T	562	81.5	594	86.1	8.5	7.1	0.58	

[1] Not temper rolled
[2] Rare-earth treated

most general result noted is that for each material, its hole expansion value greatly exceeds its total elongation determined by tensile testing. The edge extension in a hole expansion test is typically several times the tensile total elongation of either hot-[6] or cold-rolled steels.[7-11] This indicates that the hole expansion test is measuring the ductility of a material under a different strain state than that generated in a tensile test. This point will be developed further in the section covering the circle grid analysis.

Table III shows that the non-rare-earth-treated HSLA steels exhibited greater hole expansion in the de-burred edge condition. The rare-earth-treated HSLA steels showed negligible changes in hole expansion performance as a function

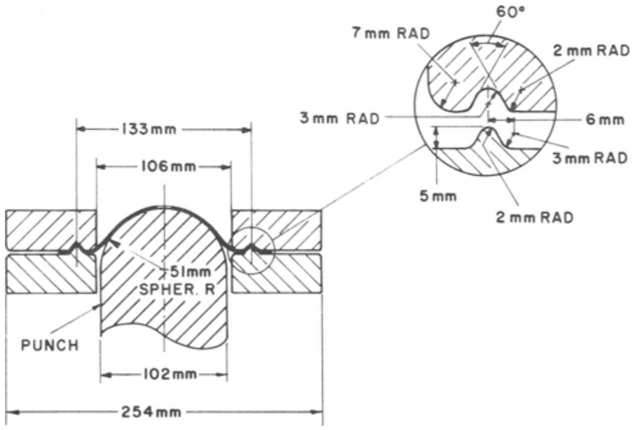

Fig. 1 — Schematic of tooling used in the hole expansion test.

Table III. Hole Expansion Performance of Steels Analyzed

Material	Hole Expansion (Pct) As-Blanked	Hole Expansion (Pct) De-Burred
HSLA 35	73.3	81.9
HSLA 45	37.2	42.5
HSLA 50	42.7	60.9
HSLA 50[1]	39.0	56.0
HSLA 50[1,2]	73.6	73.0
HSLA 60[2]	44.6	45.9
RA 70	27.6	29.8
RA 80	24.1	23.5

[1] Not temper rolled
[2] Rare-earth treated

of edge condition. These results were similar to those observed by Davies[11] on several microalloyed high-strength cold-rolled steels. Work with hot-rolled steels has shown that inclusion shape control greatly reduces the effect of edge condition on a steel's hole expansion performance.[6] Comparison of the hole expansion values for the two non-skin-rolled HSLA 50 steels with and without rare-earth treatment shows that as-blanked, the rare-earth-treated steel developed a higher hole expansion value than the non-rare-earth-treated steel in the de-burred condition. These results indicate that inclusions play a major role in the hole expansion performance of cold-rolled high-strength steels,[7,11] just as they do in hot-rolled steels.[3,6]

The RA steels developed much lower hole expansion values than the HSLA steels as expected, since they had less ductility as measured in a tensile test. The interesting thing to note is that the RA steels were also insensitive to edge condition with regard to hole expansion performance. The RA steels were not rare-earth-treated. They were not even Al killed. The reason for their edge condition response will be discussed in the next sections.

Edge Crack Analysis

For all of the steels evaluated, the cracks that developed, and defined the end of the test, were observed to run parallel to the rolling direction, *i.e.*, along the path of elongated inclusions (see Figure 2). For all but the RA steels, these cracks initiated at the hole edge. The fracture sites for both of the RA materials did not initiate, for the most part, at the hole edge. All of the de-burred RA steel samples failed first slightly away from the edge, while the as-blanked samples showed both types of failures.

Metallographic evaluations of the crack site on samples from each material were performed using an SEM equipped with EDS and WDS. All materials exhibited ductile fractures, suggesting the important role inclusions play in the failure of cold-rolled steels. In all cases, evidence of inclusions was found at the crack initiation sites. Figure 3 shows the typical remnants of MnS stringers present in the failed area of the non-rare-earth-treated steels. The RA steels contained an especially high concentration of elongated stringer inclusions. Analysis of the fracture sites of the rare-earth-treated steels revealed the presence of particles containing Mn, Ce, and/or La, in combination. The globular appearance of many of the particles indicates that some control of inclusion shape was achieved. However, some elongated stringer-type inclusions were also observed. This would indicate that inclusion shape control was not complete.

Thus, for all but the RA steels, the fracture of inclusions at the expanding sheared edges served as the nucleation sites for cracks that determine the hole expansion capabilities of these cold-rolled steels. The reason the RA steels exhibited crack initiation away from the sheared edge is discussed in the next section.

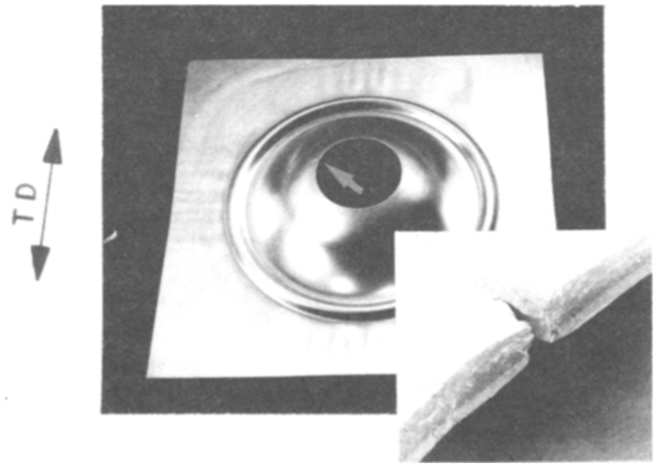

Fig. 2—Test sample and crack site for the HSLA 50 steel.

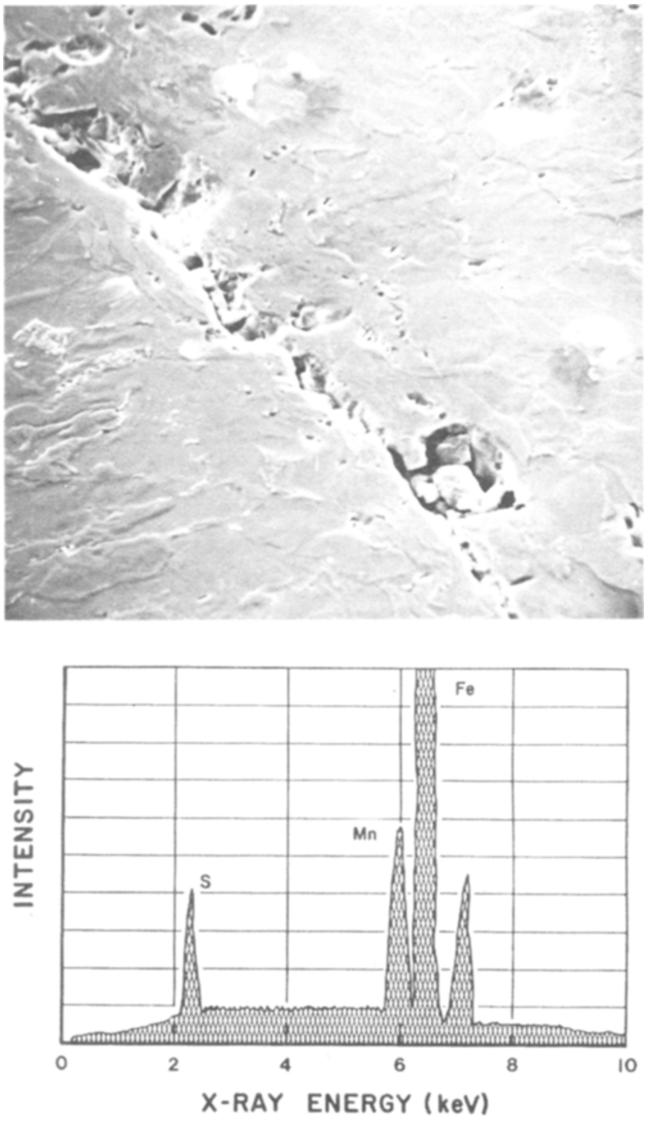

Fig. 3—Inclusion evaluation in the failure area of the RA 80 steel.

Circle Grid Analysis

Several of the hole expansion samples were electrochemically etched with 2.5 mm diameter circles prior to testing. The averages of the strains measured from three samples of the HSLA 35 steel in the de-burred condition are presented in Figure 4. Measurements were made along a radial direction extending from the edge of a hole at failure and on into the sample. A steady drop-off in major strain is observed as the measurements were taken increasingly away from the edge. Two deformation modes are observed on the tested samples: drawing near the edge, and stretching approximately 7.5 mm away from the edge and continuing into the sample. These deformation modes are bounded by a ring of plane strain deformation that extends around the hole at a distance of about 7.5 mm from the edge.

The observation of a circumferential deep-drawing strain state around the edge of the hole explains why the percent edge elongation measured in a hole expansion test is so much larger than that measured in a standard tensile test. The hole expansion test sample is a wide sheet compared to that of a tensile sample. During the hole expansion test, after initial uniform deformation, the load reaches a maximum and a diffuse neck starts to form. This diffuse neck is accompanied by contraction strains in both the radial and thickness directions. Being a wide sample, the radial strain cannot localize rapidly, so the whole neck develops gradually, and considerable extension is still possible after the onset of diffuse necking.[16] A material's resistance to thinning is characterized by its r_m value, and this is why hole expansion performance correlates well with r_m.[10,13] A condition is finally reached where a sharp localized neck can form, with the width of the neck being on the order of the material thickness. Inclusions in the material then serve as nucleation sites for cracks which end the test.

For the de-burred and some of the as-blanked RA steel samples, cracks were observed to initiate not at the hole edge, but at a short distance in from the hole edge. This location corresponds to the plane strain position on the samples. Thus, the RA steels, which had rather poor intrinsic ductility, reached their fracture stress under plane strain conditions before the onset of localized necking and failure along the hole edge. Only in some cases did the as-blanked RA steel samples have large enough initial cracks along inclusions in the shear burr that cracks propagated from those sites prior to failure in plane strain. These observations explain why the hole expansion performance of the RA steels was insensitive to edge preparation. When the shear burr and initial sources of crack nuclei were removed, the hole expansion of those materials did not improve. This was due to the plane strain ductility away from the hole edge dictating the fracture strain, and thus hole expansion.

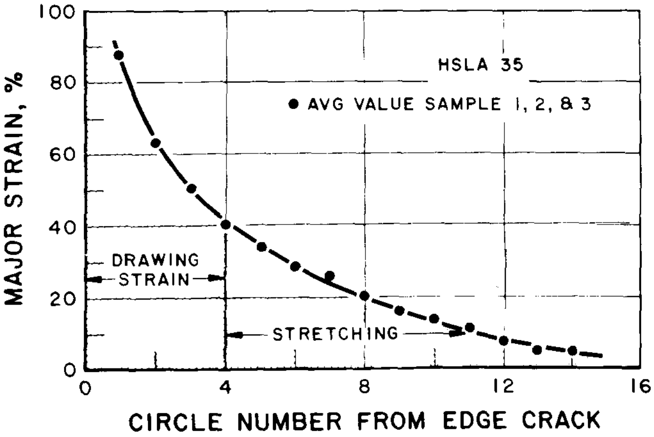

Fig. 4 — Percent major strain as a function of distance from the hole edge.

Correlation of Hole Expansion with Tensile Properties

Circle grid analysis showed that material directly around the expanding hole was in a drawing strain state. The general resistance of a material to thinning during drawing is represented by its average plastic anisotropy, r_m. Thus as noted by others,[10,13] r_m should correlate directly with hole expansion. Figure 5 presents this correlation for the entire spectrum of steels examined in the de-burred condition. Hole expansion is observed to increase with increasing r_m value in a nonlinear fashion.

Analysis of the edge cracks showed that they formed along longitudinal directions in the sheet samples. The fracture behavior of the samples was influenced by stringer inclusions which affect transverse ductility. Sample thickness also influenced the fracture strain. Thus, total elongation in the transverse direction, which is a function of sample thickness and stringer inclusion content, should directly correlate with hole expansion. The correlation between these two variables is shown in Figure 6. Hole expansion is observed

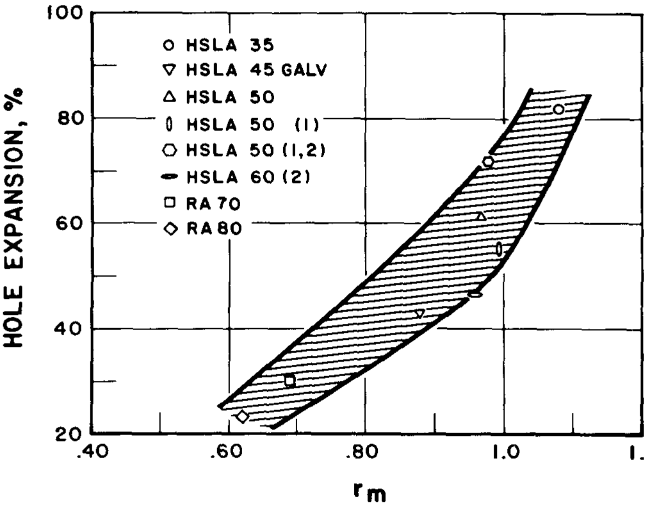

Fig. 5 — Effect of r_m on percent hole expansion. (Refer to Tables II and III for footnote notation.)

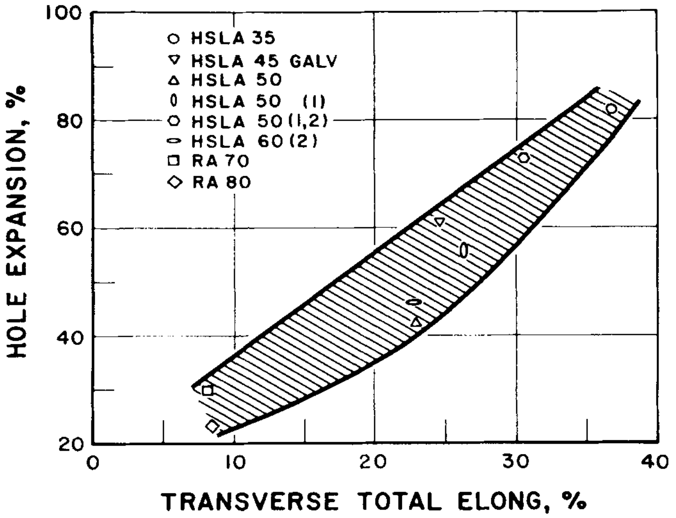

Fig. 6—Effect of transverse total elongation on percent hole expansion. (Refer to Tables II and III for footnote notation.)

to increase roughly linearly with increasing transverse total elongation.

Several functional relations among hole expansion, r_m, and transverse total elongation were explored using a multiple linear regression program. The following simple functional relationship produced a very good fit to the data from the entire range of steels tested.

$$\text{Hole Expansion (pct)} = 15 + 1.7 \times r_m \times \text{Tran. Total El. (pct)} \qquad [2]$$

Equation [2] states that hole expansion is linearly related to the product of transverse total elongation and r_m. The relationship between Eq. [2] and the actual data is presented in Figure 7. A correlation coefficient of 0.968 ± 0.034 was obtained for data that spans a broad spectrum of high-strength cold-rolled steel microstructures, ductilities, strengths, and thicknesses.

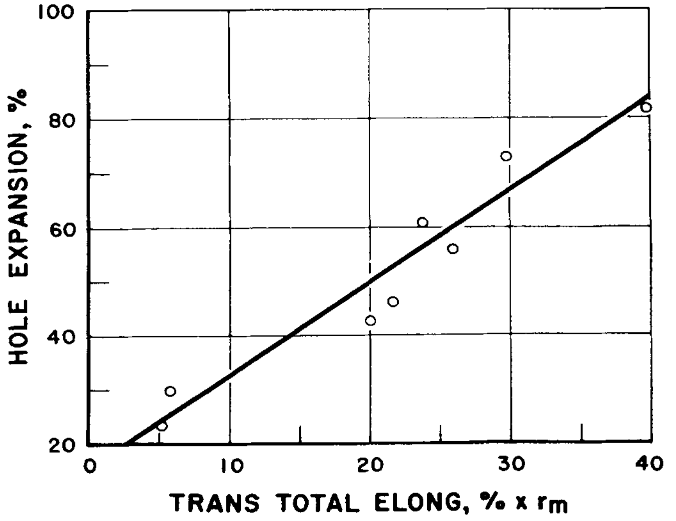

Fig. 7—Effect of the product of transverse total elongation and r_m on percent hole expansion.

Equation [2] predicts that for steels with similar ductilities (and for steels with common microstructures similar strength levels), hole expansion varies linearly with r_m. This is exactly the conclusion reached by Klein and Hitchler[10] who determined the hole expansion performance of many heats of a single variety of cold-rolled steel, which exhibited a range of r_m properties. The hole expansion test can serve as an economical procedure for determining r_m for a given steel. Conventional tensile testing to determine r_m requires three separate test directions, and is subject to a range of inaccuracies.[17] Equation [2] also predicts that the influence of r_m on hole expansion performance increases for more ductile cold-rolled steels. This effect is illustrated in Figure 8. For cold-rolled steels with total elongations of about 30 pct, each increase in r_m of about 0.1 causes an increase in hole expansion performance of greater than 10 pct.

CONCLUSIONS

Modification of stringer inclusions through rare-earth treatments improves the hole expansion performance of high-strength cold-rolled steels in two ways. With rare-earth treatment, their hole expansion behavior becomes much less sensitive to edge condition. Secondly, for a given grade of steel, rare-earth treatment significantly increases hole expansion performance, independently of edge condition.

Deformation modes generated in a hole expansion test are drawing near the hole edge and stretching farther from the edge. These modes are bounded by a ring of plane strain deformation around the hole. For steels with intrinsically low ductilities, *e.g.*, RA steels, plane strain failure away from the hole will limit their hole expansion performance.

The hole expansion performance of the spectrum of high-strength cold-rolled steels evaluated varies linearly with the product of the steels' transverse total elongation and r_m values. Among a group of steels with similar ductilities and

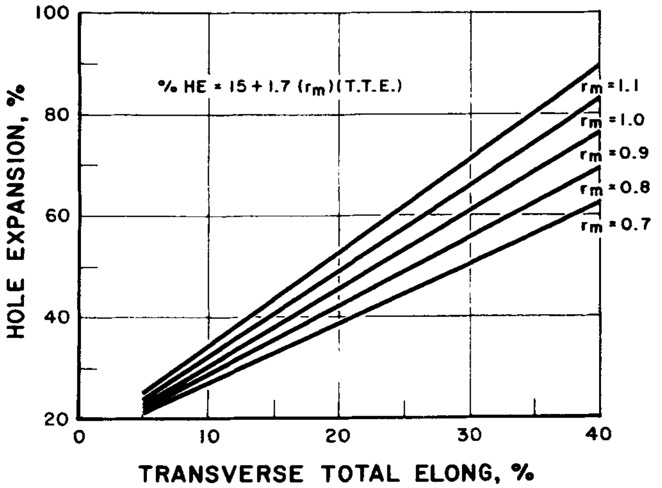

Fig. 8—Effect of r_m and transverse total elongation on percent hole expansion from linear regression analysis.

strengths, hole expansion increases linearly with increasing r_m. For cold-rolled steels with total elongations of about 30 pct, each increase in r_m of about 0.1 causes an increase in hole expansion performance of greater than 10 pct.

REFERENCES

1. J. D. Grozier: *J. of Mater.*, 1972, vol. 7, p. 3.
2. K. Matsudo, T. Shimomura, K. Osawa, M. Yoshida, and Y. Uchida: *Nippon Kokan Tech. Rep. Overseas,* 1974, no. 18, p. 1.
3. T. Matsuoka, T. Kawai, Y. Hobo, and S. Ueda: *Trans. ISIJ,* 1975, vol. 15, p. 137.
4. T. Yanaguchi and H. Taniguchi: *Nippon Kokan Tech. Rep.,* 1969, vol. 45, p. 23.
5. D. K. Uko, R. Sowerby, and J. L. Duncan: *Can. Min. Metall. Bull.*, 1977, vol. 70, p. 127.
6. R. R. Hilsen, T. E. Fine, and G. J. Hansen: *Microalloying '75,* Union Carbide Corp., New York, NY, 1977, p. 654.
7. T. R. Thomson and A. Brownrigg: *Metals Forum,* 1979, vol. 2, p. 118.
8. R. D. Adamczyk, D. W. Dickinson, and R. P. Krupitzer: SAE Technical Paper No. 830237, 1983.
9. R. R. Pradhan and E. D. Melcher: *Mechanical Working and Steel Processing Conference XXII,* Iron and Steel Society of AIME, Warrendale, PA, 1980, p. 34.
10. A. J. Klein and E. W. Hitchler: *Metals Eng. Quart.,* 1973, vol. 13, p. 25.
11. R. G. Davies: *J. Appl. Metalwork.*, 1983, vol. 2, p. 293.
12. M. Korchynsky and H. Sturat: *Symposium Low Alloy High Strength Steels,* Frese-Druck, Dusseldorf, 1970, p. 17.
13. S. P. Keeler: *Automotive Sheet Metal Formability,* Report on AISI Project No. 1201-409, June 1978, p. 41.
14. H.P. Weaver and K. J. Weinmann: *J. Appl. Metalwork.*, 1985, vol. 3, p. 381.
15. H. P. Weaver and K. J. Weinmann: *J. Appl. Metalwork.*, 1985, vol. 3, p. 391.
16. W. F. Hosford and R. M. Caddell: *Metal Forming–Mechanics and Metallurgy,* Prentice-Hall, Englewood Cliffs, NJ, 1983, p. 294.
17. Y. C. Liu: *Metall. Trans. A,* 1983, vol. 14A, p. 1199.