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MELBOURNE, VICTORIA

REPORT

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PROPERTIES OF HY-100 STEEL FOR NAVAL CONSTRUCTION

J.C. Ritter and N.J. Baldwin

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ABSTRACT

Data are presented on the chemical composition and mechanical properties of HY-100 steel manufactured by Broken Hill Proprietary Steel International, Slab and Plate Products Division and heat treated by Bunge Industrial Steels Pty Ltd. These data satisfy the requirements laid down by US Naval Sea Systems Command for first article qualification following a procedure in which explosion bulge testing is waived, but where HY-80 steel from the same source is already qualified. The Australian-made HY-100 steel is found to be eminently suitable for Royal Australian Navy ship construction.

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POSTAL ADDRESS: Director, Materials Research Laboratory
P.O. Box 50, Ascot Vale, Victoria 3032, Australia

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PROPERTIES OF HY-100 STEEL FOR NAVAL CONSTRUCTION

1. INTRODUCTION

This paper is concerned with the measurement of the mechanical properties of Australian-made HY-100 steel intended for qualification for future general applications by the Royal Australian Navy.

The steel production and qualification were undertaken following the highly successful qualification of Australian-made HY-80 grade steel, which is closely related to HY-100. Both production and qualification of these two grades are covered by US Military Specification MIL-S-16216J (SH),* which the Australian steels follow closely. This specification is administered by the US Navy Naval Sea Systems Command (NAVSEA), and is carefully monitored when outside nations qualify their own sources of supply, such as when the Australian steel was qualified for construction of the FFG-7 Guided Missile Frigate under licence from the US Navy.

Present RAN requirements for HY-100 steel are limited to the helicopter hold-down rasters being retrofitted to the FFG-7 deck. However, it was considered wise to take advantage of certain circumstances which currently prevail, namely that under NAVSEA jurisdiction HY-100 made by the same manufacturer and production route as fully qualified HY-80 may be accepted without the requirement of passing the explosion bulge test. Waiver of this test represents a very large saving in both money and time.

A second timely factor was that, arising from the establishment of the dynamic tear test and explosion bulge test capability in Australia and the welding research which led to full qualification of HY-80 plate welded by the manual metal arc process, Materials Research Laboratory (MRL) achieved recognition from NAVSEA as being competent to manage the mechanical property aspects of product qualification. The technical aspects of this work are described in detail elsewhere [1,2].

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* Current at the time of writing.

This technical work complemented the resources of Director of Naval Quality Assurance (DNQA) to provide full autonomy in qualification/first article testing to MIL-S-16216J (SH) not only for RAN requirements but also for steel which might be supplied to the US Navy or any of its licencees.

The purpose of the present work was to draw together the data on mechanical properties measured on a production sample of HY-100 steel made by the sole Australian supplier, Broken Hill Proprietary Steel International, Slab and Plate Products Division and heat treated by Bunge Industrial Steels Pty Ltd [3], hereafter abbreviated to BHP/BIS. The aim, in particular, was to report in detail the dynamic tear testing which now becomes the discriminating test in lieu of the explosion bulge test, and to establish the case for qualification of this steel without recourse to the explosion bulge test on welded plate.

2. BACKGROUND: INTERPRETATION OF HY-80/HY-100 SPECIFICATION

The proposal to qualify Australian-made HY-100 steel is based upon an interpretation of MIL-S-16216J (SH) of 10 April 1981, and on technical advice and guidance given by the US Navy technical authority [4].

In consideration of the present case, it is important to note that this specification does not require product qualification in the strict sense defined by US Navy and RAN, but calls for first article inspection and NAVSEA approval. In practice, similar procedures are required for both criteria and, either way, successful products are eligible for official qualified products listings as issued by US Navy and RAN. In view of this "qualification" is taken in the present case to mean first article testing and approval by the appropriate RAN authority, Director General of Naval Design (DGND) and DNQA.

The opportunity to waive the requirement for explosion bulge testing as part of the full first article test procedure is contained in paragraph 6.4.1 of MIL-S-16216J (SH). This states, inter alia

> *When either grade HY-80 or grade HY-100 plate material has qualified to first article test requirements, the other may be reviewed for first article approval by submitting specification required data along with full Charpy curve (longitudinal and transverse.)*

The intended interpretation of the Specification is that the required mechanical data include the tensile and Charpy/dynamic tear test results, as set out in section 3.4 of the document, but exclude the explosion bulge test as a mandatory requirement. It is implied that the grade submitted for waiver shall be made by the same manufacturer using the same production path as for the grade already qualified.

For the present qualification purpose, the requirement for mechanical data has been extended to include Charpy plus dynamic tear testing rather than the specification requirement of one or the other. It has been established that these two types of mechanical test, when considered in combination with the tensile test, provide a high level of confidence in the performance of the steel were it to be subjected to explosion bulge testing [4]. Appropriate values for 690 MPa yield strength (including HY-100) [5] have therefore been used as an additional means of evaluating this present sample of HY-100 steel against the explosion bulge test requirement.

3. MATERIAL

The material subjected to assessment was 50.8 mm thick plate. It was manufactured by Broken Hill Proprietary Steel International, Slab and Plate Products Division, Port Kembla works by the basic oxygen process. Secondary refining consisted of vacuum degassing and calcium addition, for the purpose of making fine adjustments to the content of alloying elements, lowering the content of impurity elements and modifying the morphology of the sulphide inclusions. Heat treatment was undertaken on the automated production line at Bunge Industrial Steels Pty Ltd at Unanderra, and comprised the following:

(i) austenitize at 900^{o}C for 2 h;
(ii) controlled water quench;
(iii) temper at 650^{o}C for 2.1 h;
(iv) air cool.

Subsequent plate finishing, comprising cutting of plates to correct length and width, making flatness and camber within tolerance, and priming and paint thickness measurement, was also done by Bunge Industrial Steels.

The plate submitted to analysis and all mechanical testing was sample plate No. 24689 from BHP heat No. 7703386, the serial numbers from which all manufacturing details are traceable in accordance with standard AS 1822 [3].

The whole manufacturing process was undertaken on plant and following procedures already approved by DNQA for production of HY-80 steel meeting Australian QPL requirements.

4. CHEMICAL ANALYSIS

Characteristics of Production Plate

The steel supplied by BHP/BIS is made to the one composition which satisfies the requirements in MIL-S-16216J (SH) for both HY-80 and HY-100 grades (Table 1a). This steel composition also incorporates a rider imposed by MRL which limits specifically the concentrations of gaseous and impurity elements (see Table 1b). The purpose of this rider is three-fold, as follows.

(i) Traditionally, a principal source of difference between the ingot and continuous slab casting production routes of steelmaking has been the different levels of oxygen, nitrogen and hydrogen in the final solid product, given an identical molten steel. Consequently, MIL-S-16216J (SH) required separate qualification of each route. By limiting the contents of oxygen, nitrogen and hydrogen to appropriately low levels which eliminate this difference, a single qualification can be granted to the whole production facility.

(ii) By controlling hydrogen to low levels, it is possible to avoid hydrogen flaking of slab surfaces and ultimately poor surface on the finished plate.

(iii) By restricting sulphur, oxygen and hydrogen to low levels in combination with correct levels of major alloying elements, it is possible to ensure that exceptionally high levels of crack toughness are maintained in all production batches.

5. DYNAMIC TEAR TESTING

5.1 Testing Machine

The existing drop weight tower at MRL was extensively modified to conform with ASTM E604-82 for dynamic tear testing [6]. Steps were taken to eliminate sources of machine error and variability, as set out below.

(i) The machine and tup were carefully aligned in order to minimize friction effects.

(ii) An adjustable striker nose and specimen locating jigs were adopted to give precise alignment during impact. The specimen locating jig was a quick-action type to assist in minimizing specimen temperature drift after removal from the cooling bath.

(iii) Provision was made for measuring tup velocity through 100 mm of displacement. This large travel above the anvil stops ensured that tup velocity could also be measured after specimen fracture was completed.

(iv) Instrumentation used an optoelectronic system, to enable tup velocity to be determined before, during and after specimen contact. This had a resolution of 0.2 mm in location and 0.1 ms^{-1} in velocity. The latter translates into 30 Joule with the tup and drop used. Accurate records of incident tup energy, residual tup energy, and of events during specimen fracture, were derived from tup displacement vs time measurements made on a digital transient storage oscilloscope.

(v) In all tests, the incident velocity of the tup was checked against calculated free-fall velocity (corrected for friction). The residual energy was checked against the compression of calibrated crusher blocks made of copper tube. Agreement between both checks and the instrumented results is normally better than 5%, and approaches 1% for a given test material.

5.2 Results for HY-100 Steel

Tests on the HY-100 sample plate No. 24689 were carried out in accordance with ASTM E604-82, using 16.0 mm thick specimens having impressed notches. Specimens were of transverse orientation relative to the rolling direction of the plate, i.e. with notches in the longitudinal direction. This coincides with the T-L orientation of the Charpy impact specimens.

The following test conditions were used:

(i) tup mass 37.19 kg,

(ii) tup incident velocity 8.5 ± 0.1 m/s,

(iii) test temperature -40°C as required by MIL-S-16216J (SH) except for one test conducted at -70°C and using a 27.94 kg tup.

The results of these tests are given in Table 2 and the trends of the energy-temperature transition curves are shown in Fig. 1.

One consequence of the limited amount of material available for test from plate 24689 was that insufficient dynamic tear test data are available to describe the complete energy-temperature transition curve for this steel. It was considered to be worthwhile to determine such a curve in order to compare the transition behaviour determined by dynamic tear test with that from the Charpy test. The extra data were obtained on material from another heat of HY-100 steel from which a larger number of test specimens could be prepared. The rationale for this was the high degree of consistency in properties of HY-80 steel established by a long production record of BHP/BIS.

Further dynamic tear tests were conducted on samples from BHP/BIS Heat No. 17747726 of HY-100 steel. A heavier tup was used than with plate 24689, namely 112 kg mass, in conjunction with a reduced drop height of 2.0 m; these parameters were still within the range permitted by ASTM E604-82, and led to a larger, and therefore more satisfactory, residual tup energy after impact and fracture of the test specimen.

These further test results are included in Fig. 1, and reveal a transition temperature almost identical with plate 24689, along with an upper shelf energy some 50% higher than that of plate 24689, and 360% higher than the specification value.

6. TENSILE AND CHARPY TESTS

These tests were undertaken by Bunge Industrial Steels Pty Ltd under NATA registration. Results are given in Tables 3 and 4. The curves relating Charpy impact energy with temperature curves are plotted in Fig. 2. All test values are markedly higher than the specification minima, and suggest that at temperatures as low as -84°C the steel is substantially in the upper shelf regime of behaviour. Material from the front end of the plate is more anisotropic than material from the back end.

7. EXPLOSION CRACK STARTER TESTS

A number of explosion bulge crack starter tests were conducted on samples of this same HY-100 plate by Snowy Mountains Engineering Corporation in August-September 1986 under contract to Australian Submarine Corporation [7].

These tests were exploratory in nature, as the aim was to qualify steel of Swedish design for the Royal Australian Navy, New Construction Submarine Project. No attempt, therefore, was made to conduct tests specifically for qualifying the HY-100; however conditions of test were valid, and enabled useful information to be obtained for the present purpose.

Results of the tests are given in Table 5. One of the tests on unwelded plate was taken through 5 blasts and achieved 23.7% thinning at the centre of the plate bulge, compared with 14% minimum called for unnotched welded plate in MIL-S-16216J (SH). While it did not test the plate in the strict sense of the specification, because of the absence of a full through-thickness weld and concomitant heat-affected zones in the plate, the result is nevertheless a strong indication of satisfactory plate. The value of 23.7% thinning, with small through-thickness cracks, compares most favourably with an unnotched, unwelded panel of HY-80 plate which was tested in other work [2,3] to 24.6% thinning without sign of cracking. The small cracks in the present test plate were probably initiated by brittle starter weld beads, features which were absent on the HY-80 test plate.

8. DISCUSSION

8.1 Evaluation against Benchmark Properties

Previous work by the authors [4,5] has followed a different approach to establishing fitness for qualification, by determining those mechanical properties which are commensurate with passing the explosion bulge test. These particular values of mechanical property are identified as 'benchmark' values, to distinguish them from the values specified in MIL-S-16216J (SH). This approach to steel qualification argues that, once the value of yield stress is designated, the explosion bulge test is the discriminating test in respect of all toughness-related properties.

Extensive practical data on explosion bulge testing of HY-100 steel and concomitant mechanical test data - tensile, Charpy and dynamic tear - were ranked in order to extract benchmark values for these tests. These benchmark values were the properties measured on samples of plate which just passed the bulge test. The virtue of this benchmark approach is that it draws upon sets of consistent data, in contrast with qualification by MIL-S-16216J (SH) which calls for the various mechanical properties which are set according to a somewhat arbitrary basis, and not unified by an over-riding, discriminating test.

A comparison of properties of sample plate No. 24689 with benchmark values derived for plate of 690 MPa yield strength [4,5] is set out in Table 6. Although these benchmark values are more severe than the MIL-S-16216J (SH) specification requirements (compare Table 6 with Tables 2 and 4), it is seen that plate 24689 exceeds all by a comfortable margin (noting that 0.2% proof stress must match the benchmark property). Because of the experimental origin of the benchmark properties, these margins of pass can be translated to a clear pass in the explosion bulge test with a high degree of confidence.

8.2 Evaluation Against First Article Qualification Requirements

Examination of the present chemical analysis and mechanical test results has shown the following:

(i) the chemical analysis complies with the requirements of the specification MIL-S-16216J (SH) and rider imposed by MRL (Tables 1a, 1b);

(ii) the dynamic tear energy results have very small scatter and are well in excess of the specified minimum value (Table 2);

(iii) the tensile test results fully comply with the specification (Table 3); and

(vi) the Charpy impact values for both orientations exceed the specified values by large margins at all temperatures (Table 4).

8.3 General

Results of the dynamic tear tests determined on the later batch of HY-100 steel, tested with a heavier tup but still within specification, resulted in a significantly different but even more favourable temperature transition curve as shown in Fig. 1. It is likely that the differences in tup mass and impact velocity used in the two sets of dynamic tear tests may have a small influence on the upper shelf energy attained (Fig. 1), but would not account for the whole difference. Examination of the fracture faces of broken halves of all specimens tested at or above -50°C showed a fully ductile condition. Therefore, it is considered that the range in dynamic tear energy at -40°C from 1140 to 1700 J is a fair indication of the likely upper shelf behaviour of this steel.

Although the explosion crack starter tests on the unwelded HY-100 plate were not part of any qualification requirement, they clearly demonstrate very high levels of crack toughness under explosive loading conditions. In particular, test 1 of Table 5 resulted in 23.7% thinning with only small through-thickness cracks. This is well in excess of the 14% required by MIL-S-16216J (SH) for an unnotched welded plate, and compares very favourably with the 25.8% thinning achieved previously on HY-80 unwelded plate [1,2] although the latter was not penalized by deposition of a crack-starter weld bead.

Useful information is also obtained from the crack starter tests on welded HY-100 plate, even though the tests gave strictly "fail" results because of premature failure of the welds. In all three tests (tests 3, 4, 5 of Table 5) the parent plate sustained minimal cracking when complete fracture occurred in the adjacent weld. This behaviour includes test No 4 (Table 5) in which the amount of plate thinning adjacent to the weld reached 6.7% which is comfortably in excess of the minimum 6.0% implied in the specification.

Thus, these explosion test results show unequivocally that the weld heat-affected zone of the HY-100 plate has adequate properties under explosive loading. This finding constitutes one of the key points arising from explosion testing of welded plate, and therefore provides strong supportive validation of the steel.

Comparison of the present test results against the benchmark properties set by the MRL philosophy for passing the explosion bulge test, is very favourable for the HY-100 steel under examination. While these benchmarks are quite outside the Specification requirements, the good passes confirm that in practical terms, the plate will perform as well as the Australian HY-80.

In summary, all of the above items are considered to provide satisfactory evidence that the present sample of HY-100 steel should qualify according to paragraph 6.4.1 of MIL-S-16216J (SH), with additional supportive evidence from the explosion crack starter tests. Moreover, the toughness properties are equally good as those of previously studied Australian HY-80 steel [1,2] and, since that steel which had almost identical composition passed the whole explosion bulge test program with outstanding success, there is good reason to expect similar performance from the present sample of HY-100.

Generalizing upon the results from sample plate No. 24689 and dynamic tear test results of plate from BHP/BIS Heat No. 7747726, the HY-100 steel made by BHP/BIS is assessed as being eminently suitable for construction of ships and submarines for the Royal Australian Navy.

9. CONCLUSION

It is concluded that the HY-100 steel made by BHP/BIS is of high quality. The properties obtained on sample plate No. 24689 are amply sufficient for first article qualification, based on existing HY-80 steel from that source, without the need for explosion bulge testing as permitted by MIL-S-16216J (SH). It is assessed as being eminently suitable for RAN construction where HY-100 grade steel is called for.

10. ACKNOWLEDGEMENTS

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TABLE 1a

Chemical Analyses

Element (wt%)	MIL-S-16216J (SH) Grade HY-80	HY-100	BHP/BIS Target	Plate 24689
C	0.10 - 0.20	0.10 - 0.22	0.12 - 0.14	0.18
P	0.020 max	0.020 max	0.015 max	0.011
Mn	0.010 - 0.45	0.10 - 0.45	0.25 - 0.35	0.26
Si	0.12 - 0.38	0.12 - 0.38	0.20 - 0.30	0.25
S	0.020 max	0.020 max	0.002 - 0.008	0.003
Ni	1.93 - 3.32	2.67 - 3.57	2.8 - 3.1	2.95
Cr	0.94 - 1.86	1.29 - 1.86	1.45 - 1.65	1.50
Mo	0.17 - 0.63	0.27 - 0.63	0.40 - 0.50	0.37
V	0.03 max	0.03 max		0.010
Ti	0.02 max	0.02 max		0.005
Cu	0.25 max	0.25 max		0.016
Al			0.02 - 0.04	

TABLE 1b

Rider to MIL-S-16216J (SH)

Element	Requirement	Plate 24689
S	0.002 - 0.010 wt%	0.003 wt%
O	50 ppm max (active plus combined)	20 ppm
N	110 ppm max	67 ppm
H	3 ppm max	0.2 ppm

Note: All values are on product analysis, and apply to plate more than 32 mm (1-1/4 inch) in thickness.

TABLE 2

Dynamic Tear Tests, Plate 24689

Test	Temperature (^{o}C)	Absorbed energy to fracture (J)	Specification MIL-S-16216J (SH) (J)
1	-40	1194	678 min
2	-40	1193	" "
3	-40	1140	" "
4	-70	489	-

TABLE 3

Tensile Properties

Location of test piece	Front end	Back end	Specification MIL-S-16216J (SH)
Yield stress 0.2% offset (MPa)	790	793	689–793
Ultimate tensile strength (MPa)	877	895	record for information
Elongation on 2 inch (4 diam gauge length) (%)	28	22	18 minimum
Reduction of area (%)	71	69	45 minimum

All data determined by Bunge Industrial Steels Pty Ltd (NATA approved)

TABLE 4

Charpy Impact Properties

Plate	Direction	Temp. (^{o}C)	Results (J)	Av. (J)	Specification MIL-S-16216J(SH)
24689F	L	21	152, 154, 174, 194	170	
		- 1	168, 170, 178, 183, 192	178	
		-17.8	153, 160, 162, 182, 193	170	
		-51	150, 150, 154, 155, 160	154	
		-84	129, 129, 132, 140, 145	135	
	T	21	122, 132, 134, 134, 156	136	
		- 1	116, 126, 116, 130, 136	125	
		-17.8	112, 120, 126, 128, 132	124	75
		-51	104, 114, 117, 120, 124	116	
		- 84	94, 98, 101, 110	101	41
24689B	L	21	134, 160, 162, 164, 190	162	
		- 1	130, 142, 144, 145, 152	143	
		-17.8	138, 148, 154, 170, 173	157	
		-51	114, 115, 110, 140, 150	126	
		-84	95, 100, 111, 116, 118	108	
	T	21	152, 154, 158, 160, 162	157	
		- 1	138, 156, 158, 162, 164	156	
		-17.8	130, 131, 132, 135, 140	134	75
		-51	124, 126, 126, 130, 137	129	
		-84	78, 91, 94, 102, 103	94	41

Data supplied by Bunge Industrial Steels Pty Ltd (NATA approved). All specimens 10 x 10 mm; ASTM profile striker used.

F = front end of production plate
B = back end of production plate

TABLE 5

Explosion Crack Starter Test Results

Test No.	Plate condition (Plate 24689)	Total blasts	Accumulated		Comment
			Bulge (mm)	Thinning (%)	
1.	Unwelded, brittle weld bead as crack starter	5	145	23.7	Successful; small through-thickness cracks
2.	Unwelded, same as 1	3	87	10.0	Successful; minor cracking
3.	Welded, 12018-M2 electrodes	2	26	4.6	Failed; complete separation along weld, minimal cracking in plate
4.	Welded, 12018-M2 electrodes	3	83	6.7	Failed; complete separation along weld, minimal cracking in plate
5.	Welded, 11018-M1 electrodes	2	69	5.2	Failed; major cracking in weld, minimal cracking in plate

TABLE 6

Evaluation Against Benchmark Properties

Property	Plate 24689 (average value)	Benchmark Value
0.2% proof stress (MPa)	792	689–793
Tensile elongation on 4 diameter g.l. (%)	25	18
Charpy impact energy with ASTM striker (J)	145 at -18°C 105 at -84°C	90 at -18°C 41 at -84°C
Dynamic tear energy at -40°C (J)	1176	680

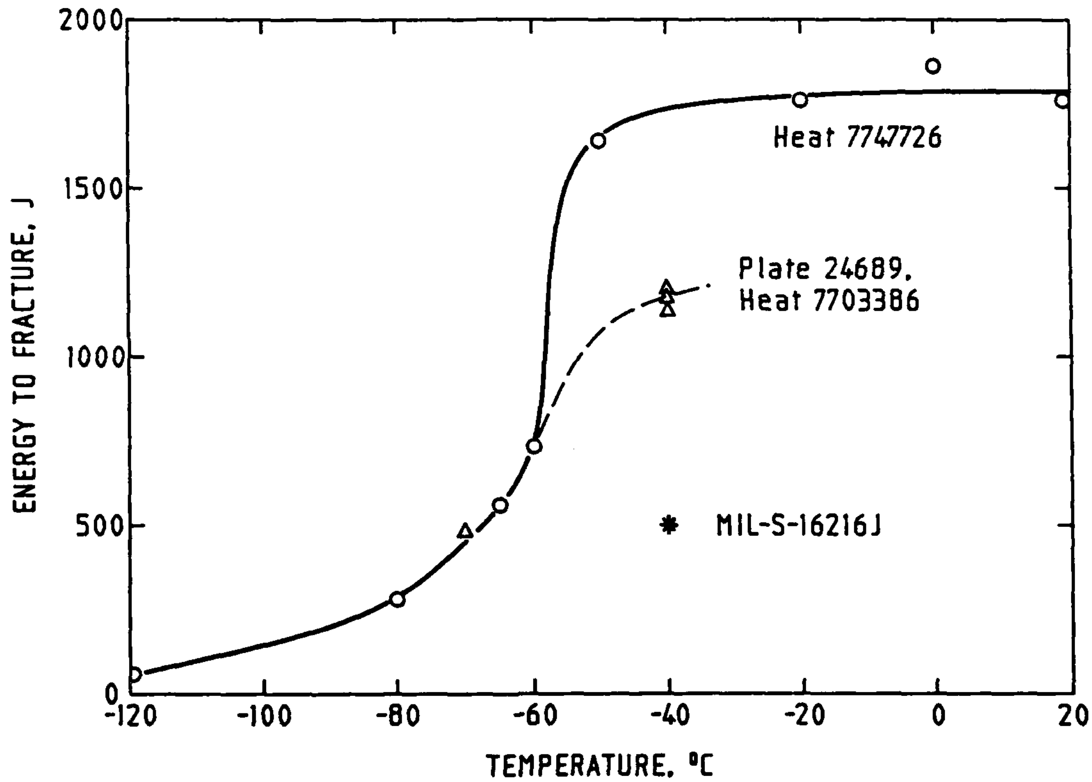

FIGURE 1 Dynamic tear properties of HY-100 steel made by BHP/BIS. Triangles are data from Plate 24689 of Heat 7703386; circles are data from plate of Heat 7747726.

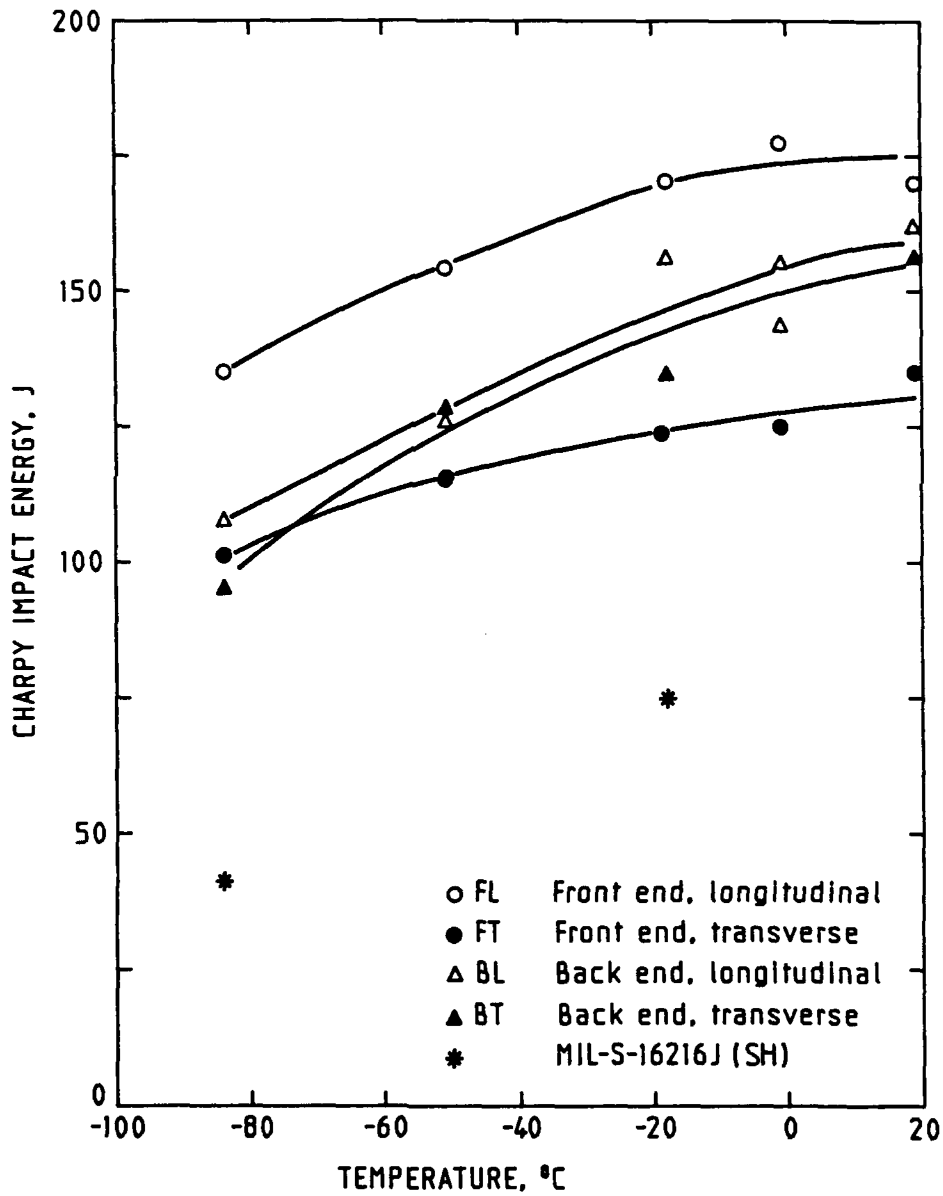

FIGURE 2 Charpy V-notch impact data on HY-100 steel made by BHP/BIS.

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AUTHOR(S)

J.C. Ritter and N.J. Baldwin

CORPORATE AUTHOR

Materials Research Laboratory, DSTO
PO Box 50
Ascot Vale Victoria 3032

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