The Influence of Grain Boundary Fracture on Fragmentation Behaviour — Part 2

George M. Weston and Norbert M. Burman

MRL Technical Report
MRL-TR-91-36

Abstract

The effect of grain boundary sulphide precipitation on fragmentation performance has been investigated for low alloy steel cylinders tempered at selected temperatures within the range 150°C to 550°C. It was found that, as expected, increased cylinder hardness generally increased the fineness of cylinder fragmentation for both specially heat-treated cylinders with sulphide precipitates present at grain boundaries, as well as standard untreated cylinders. Over the range of tempering temperatures used, the specially treated cylinders, however, showed generally finer fragmentation as measured by a 15% to 30% increase in the Length Normalized Payman Fragmentation Parameter measured for these cylinders. Both fractographic and metallographic evidence indicated that the presence of grain boundary sulphide precipitation assisted in cylinder breakup for steel of the type tested.

MATERIALS RESEARCH LABORATORY

Published by

Materials Research Laboratory
Cordite Avenue, Maribyrnong
Victoria, 3032 Australia

Telephone: (03) 319 3887
Fax: (03) 318 4536

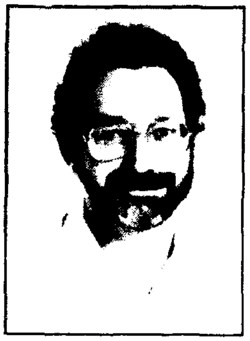
AR No. 006-829

APPROVED FOR PUBLIC RELEASE

Authors

George M. Weston

George Weston has worked at MRL since graduating from RMIT in 1970 obtaining a Diploma in Secondary Metallurgy. During this period he has been involved in several areas of research namely, solidification, secondary steel making, metal surfacing and while on secondment in the UK aspects of aircraft sabotage. Recent research has involved the interaction of materials and explosives within the Materials Division.



N.M. Burman

Norbert Burman graduated with B App Sc (Hons) (Adelaide) and PhD (Monash) degrees in 1970 and 1976 respectively. Since he joined MRL in 1975, he has undertaken research into the interaction of explosives and materials, and in particular the design, optimization and performance evaluation of high explosive munitions. He is currently working as a Principal Research Scientist within the Materials Division of MRL.

Contents

The Influence of Grain Boundary Fracture on Fragmentation Behaviour — Part 2

1. *Introduction*

In earlier work [1], the influence of grain boundary sulphide precipitation on the fragmentation behaviour of a metallurgically clean, low-alloy, Electro Slag Refined (ESR) steel was investigated using explosive testing of cylinders which had been tempered to two hardness levels (330 and 430 HV30). Statistical and metallographic evidence in the form of overheating facets on the fracture surface, indicated that the presence of this grain boundary phenomenon assisted in promoting finer fragmentation in steel of this composition. The results of these tests were, however, somewhat inconclusive due to the limited number of cylinders tested and the overlapping of some results probably due to natural scatter, a not uncommon feature of fragmentation testing.

Walsh [2] is an independent study, used an AISI 1340 steel to investigate the relationship between fragmentation performance and steel hardness. His results showed a power law relationship existed between cylinder hardness and fragmentation fineness, the finest fragmentation being observed in those steel cylinders which had been tempered to the highest hardness.

After allowing for the compositional differences between the steels used for the above studies a broad comparison of the results is still possible. This comparison suggests that for the ESR fragmentation study [1], factors such as variations in material hardness, the limited range of the test program and the natural scatter in the fragmentation results, could in themselves have accounted for the finer fragmentation observed in the grain boundary modified steel. The work of Walsh [2], however, suggests that relatively small changes in initial cylinder hardness are unlikely to be the exclusive cause of the magnitude of the change observed in the fragmentation performance.

The present work was initiated to extend the earlier ESR grain boundary sulphide study [1] to include a wider range of cylinder hardnesses within the useful range of mechanical properties for a fragmenting munition steel, and to investigate the role of grain boundary sulphide precipitates in promoting finer fragmentation.

2. *Experimental*

Fragmentation test cylinders were machined from the same batch of low sulphur ESR gun steel used in the earlier study on fragmentation behaviour [1] and ESR overheating experiments [3, 4]. The composition of this steel is given in Table 1. Cylinder blanks, designed ESF 1 to 10 were heated to 1400°C and held at this temperature for one hour under an argon atmosphere and then furnace-cooled at approximately 12 to 18°C/min. This heat-treatment is known to result in extensive grain boundary sulphide precipitation at the high temperature austenite grain boundaries [1, 3, 7].

Table 1: *Composition of Low Sulphur ESR Steel*

C	Si	Mn	S	P	Ni	Ct	Mo	V	Al
0.43	0.47	0.70	0.0014	0.009	3.3	1.2	0.70	0.15	0.013

Amounts are in wt%.

The above blanks, (ESF 1 to 10), along with an equal number of additional blanks (ESF 14 to 23) which had not been treated to produce grain boundary precipitation, were austenitized at 850°C for one hour and then oil quenched. Two blanks from each of the above cylinder sets were selected for a tempering heat-treatment over the range 150 to 500°C to produce a range of cylinder hardness values. The above heat-treatment details along with the masses, hardness values and percentage of each cylinder recovered after detonation are provided in Table 2.

For the sake of simplicity in the remaining text, cylinders given the additional high temperature heat-treatment will be referred to as "special" and those given the conventional heat-treatment, as "standard".

Test cylinders were machined to the final dimensions shown in Figure 1. These dimensions were selected to maximize the likely influence of grain boundary sulphides by accentuating the component of tensile fracture in the overall fragmentation event by using a relatively thick wall and low high explosive (HE) charge mass to steel mass ratio (C/M). Cylinders were filled with Composition B HE (55 RDX, 45 TNT, 1 beeswax) and detonated in air in a fragmentation pit using water as the retarding medium [5]. Fragments recovered after detonation were cleaned by ultrasonic vibration in a hot Alconox solution [6] to remove explosive debris and light rust from the fracture surfaces. Randomly selected fragments were examined metallographically using established techniques to reveal the extent of grain boundary precipitation

[1, 3, 4] as well as the degree of grain boundary crack initiation. The fracture surfaces of other fragments were examined by both optical and scanning electron microscopy.

Table 2: ESF Series — Heat Treatments, Hardness, Cylinder Masses and Fragment Recoveries

Cylinder Number	Special High Temperature Heat Treatment*	Tempering Temperature# °C	Hardness HV30	Cylinder Mass (g)	Fragment Recovery %
ESF–1	Yes	150	561	430.0	97.09
ESF–2	Yes	150	561	452.1	98.83
ESF–14	No	150	547	457.8	99.40
ESF–15	No	150	543	452.2	99.35
ESF–3	Yes	200	540	450.2	90.03
ESF–4	Yes	200	537	452.7	99.74
ESF–16	No	200	523	451.0	99.29
ESF–17	No	200	523	454.0	99.71
ESF–5	Yes	300	499	450.7	99.17
ESF–6	Yes	300	511	453.0	99.17
ESF–18	No	300	502	449.2	99.14
ESF–19	No	300	484	453.4	99.77
ESF–7	Yes	400	473	451.9	99.17
ESF–8	Yes	400	476	448.1	98.85
ESF–20	No	400	479	449.3	99.66
ESF–21	No	400	472	450.6	98.80
ESF–9	Yes	500	441	454.0	99.67
ESF–10	Yes	500	446	450.8	99.53
ESF–22	No	500	439	451.6	100.13
ESF–23	No	500	432	440.4	99.87

* Heated under argon for one hour at 1400°C then furnace cooled.
\# All cylinders austenitized at 850°C, oil quenched.

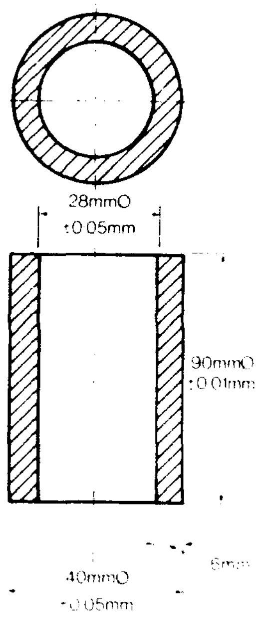


Figure 1: Dimensions of Fragmentation Cylinder.

3. *Results and Discussion*

Details of the length normalized Payman fragmentation parameter derived for each cylinder and the percentage variation of the average value for the standard series from the average value of the special series, at each tempering temperature, are shown in Table 3. The variation in the Payman fragmentation parameter for each series of cylinders over the range of tempering temperatures investigated is shown schematically in Figure 2.

Table 3: Length Normalized Payman Parameters for ESF Cylinders at Five Tempering Temperatures

Cylinder No.	Special Treatment*	Length Normalized Payman Parameter: Actual	Length Normalized Payman Parameter: Mean	% Difference	Temperature °C
ESF-1	Yes	2.5	2.25	51	150
ESF-2	Yes	2.0			
ESF-14	No	0.99	1.09	106	
ESF-15	No	1.20			
ESF-3	Yes	1.99	2.06	26	200
ESF-4	Yes	2.14			
ESF-16	No	1.33	1.52	36	
ESF-17	No	1.7			
ESF-5	Yes	1.61	1.71	19	300
ESF-6	Yes	1.81			
ESF-18	No	1.31	1.39	23	
ESF-19	No	1.47			
ESF-7	Yes	1.62	1.52	15	400
ESF-8	Yes	1.42			
ESF-20	No	1.45	1.30	17	
ESF-21	No	1.14			
ESF-9	Yes	1.18	1.25	33	500
ESF-10	Yes	1.33			
ESF-22	No	1.01	0.84	49	
ESF-23	No	0.68			

* Heated under Argon for one hour at 1400°C then furnace cooled.

Examination of these results indicates that incrementally lowering the tempering temperature, and consequently increasing cylinder hardness generally resulted in finer fragmentation and a consequent increase in the Payman fragmentation parameter for both series of cylinders. Table 3 also shows that the average Payman fragmentation parameter value for the standard cylinders was 15 to 30% lower than that of the special cylinders over most of the tempering temperature range and typically 50% below that of the special cylinders at the lowest tempering temperature (highest cylinder hardness). As shown in Figure 2, for these higher hardness cylinders, the trend towards finer fragmentation with increasing cylinder hardness was significantly reversed in the standard cylinder series, while the consistent incremental increase in the fineness of fragmentation with increasing cylinder hardness for the special cylinders was maintained.

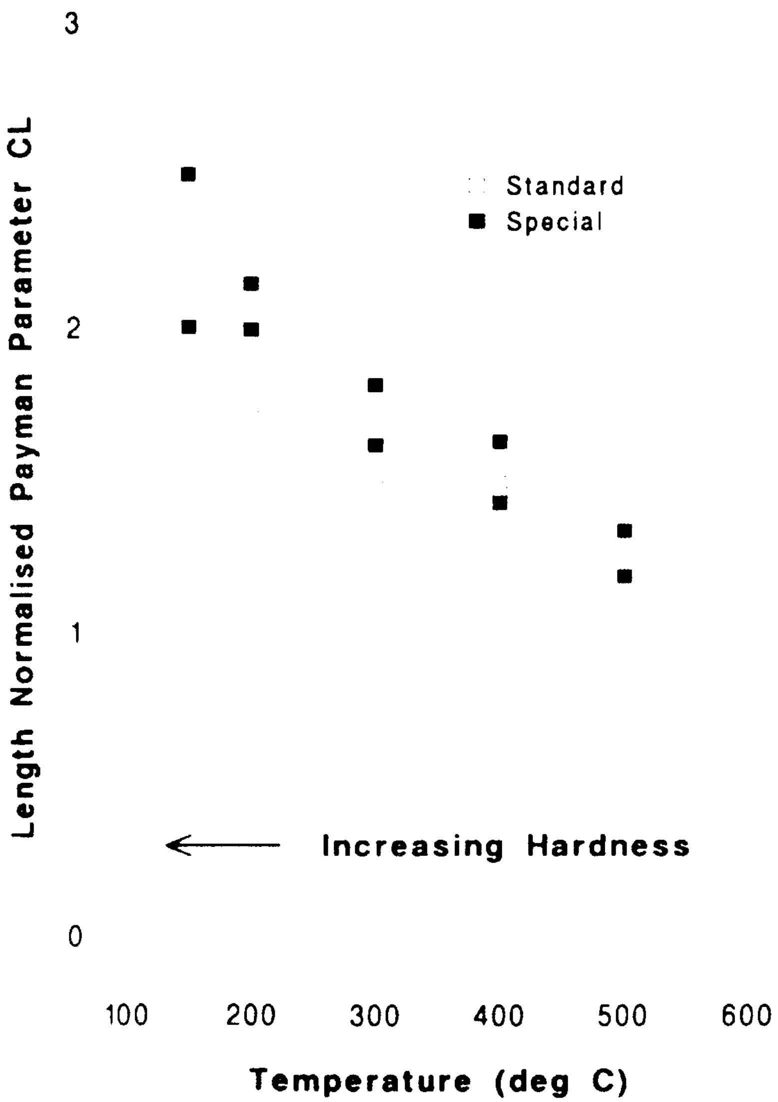


Figure 2: Variation of length normalized Payman parameter with tempering temperature for standard and special test cylinder series.

Fractographic examination of fragments from the special cylinder series showed that approximately 30 to 40% of all fragments which exhibited radial fracture, had some areas of grain boundary fracture; that is, they had a faceted fracture surface appearance as typified in Figure 3. An earlier grain boundary sulphide fragmentation study [1] reported a similar level of fragments with grain boundary fracture. The percentage of fragments featuring grain boundary fracture appeared to be independent of tempering temperature. However, as grain boundary facets tend to become flatter and less well defined with increasing cylinder hardness [7], the low magnification inspection used to examine fracture surfaces may have underestimated the percentage of faceted fracture in high hardness cylinders.

Figure 3: Transverse surface showing faceted fracture along the pre-existing grain boundary sulphide arrays. Scanning electron fractograph. X25.

In contrast, the transverse fracture surfaces of all standard cylinders exhibited a very high proportion of shear failure, with some 8% to 12% of fragments showing small areas of transgranular ductile fracture on at least one of the fracture ends. All longitudinal fracture surfaces showed only a shear failure mode.

Metallographic examination of fragments recovered from the special cylinders revealed some occurrences of subsurface intergranular cracks associated with the sulphide precipitation, running in the longitudinal cylinder direction, Figure 4, a feature also observed in earlier work [1]. Over the tempering temperature range, white etching bands, which are normally associated with adiabatic shear fracture, were observed beneath both the longitudinal and transverse shear surfaces of both standard and special cylinders. The extent of the adiabatic shear, mid-radial and subsurface cracking was, however, found to be more pronounced in fragments recovered from cylinders tempered at lower temperatures.

Figure 4: Section of fragment etched to reveal grain boundary sulphides showing extensive longitudinal intergranular cracking in some fragments. X20.

It has been previously established that for steels which produce relatively coarse fragmentation [8], the expected scatter in fragmentation parameters is approximately ± 20%. With the possible exception of the test results of the cylinders of highest hardness, the differences between the two series of cylinders, 15 to 30% over the majority of the tempering temperature range, may not be considered highly significant. The general trend in the Payman fragmentation parameters for cylinders with induced grain boundary sulphide precipitation is however, approximately 20% higher, which is consistent with that reported in earlier work for cylinders with similar hardness levels [1]. This result would suggest that, independent of cylinder hardness, an increase in the fineness of fragmentation of approximately 20% can be expected if extensive grain boundary sulphide networks are present in a comparable low alloy steel.

Walsh [2] in his investigation of the interrelationship between cylinder hardness and fragmentation in a AISI 1340 steel showed that increasing cylinder hardness (lowering tempering temperature), increased the fineness of fragmentation in steel cylinders having a duplex microstructure (grain boundary ferrite). In this study it was reported that the presence of grain boundary ferrite assisted crack initiation and provided a preferential low energy pathway which assisted transverse crack propagation.

It has been established that grain boundary sulphide precipitation can also significantly reduce the notch toughness of low alloy steels [4, 7]. As the microstructure of the steel used in this study was essentially free of grain boundary ferrite, the presence of manganese sulphide (MnS) precipitates would have produced a similar mechanism to that observed for grain boundary ferrite [2] by providing preferential crack initiation sites and preferred low-energy paths for the propagation of transverse tensile fracture. A number of studies [9, 10] have found that the contribution of tensile failure to cylinder breakup increases with increasing fineness of fragmentation.

In the absence of a grain boundary phase, several other mechanisms have been reported to contribute to cylinder breakup and hence an improvement in the fineness of fragmentation with increasing cylinder hardness. In the present study and elsewhere [2, 11] the level of adiabatic shear failure has been observed to increase with increasing cylinder hardness and consequently assist in fragmentation cylinder breakup. Inclusions have also been observed to initiate mid-radial and subsurface cracks, features observed to become more prevalent with increasing cylinder hardness [2]. In the present study, both the presence of adiabatic shear and the number of mid-radial and subsurface cracks increased with increasing cylinder hardness except for standard cylinders ESF 22 and ESF 23 where fewer subsurface and mid-radial cracks were observed.

As a very clean ESR steel was used in this study the number and size of inclusions was substantially lower than that of commercially available steels used in fragmenting munitions. Walsh [2] also observed a higher incidence of inclusion initiated cracks in cylinders of higher hardness where the trend towards finer fragmentation with increasing cylinder hardness was maintained over a similar range of tempering temperatures. The role of inclusions in providing crack initiation sites appears to assume greater importance with increasing cylinder hardness. The occurrence of this phenomenon in the ESR steels used in this study may explain the sudden reversal in the trend towards finer fragmentation with increasing cylinder hardness observed with the two standard cylinders at the highest hardness level.

4. *Conclusions*

For both the special and standard cylinders, increasing cylinder hardness levels generally resulted in an increase in the fineness of fragmentation and a consequent increase in the length normalized Payman fragmentation parameter, except for the standard cylinders of highest hardness where this trend was reversed.

Over the range of tempering temperatures examined, a 15 to 30% lower Payman fragmentation parameter was evaluated for the standard cylinders series without induced grain boundary precipitation compared with that observed with the special cylinder series.

Both statistical and metallographic evidence in the form of numbers of grain boundary facets indicates that MnS precipitation at the high temperature austenitic grain boundaries assists transverse fracture during cylinder breakup.

5. *References*

1. Weston, G.M., Walsh, B.E. and Andrew, A.C. (1982).
   The influence of grain boundary sulphides on fragmentation behaviour (R) (MRL Report MRL-R-852) (Restricted). Maribyrnong, Vic.: Materials Research Laboratory.

2. Walsh, B.E. (1977).
   An assessment of the natural fragmentation of several candidate materials for the production of 81 mm mortar bomb casings (Restricted). Maribyrnong, Vic.: Materials Research Laboratory.

3. Andrew, R.C., Weston, G.M. and Yellup, J.M. (1980).
   Spall fracture via grain boundary (Restricted) (MRL Report MRL-R-799). Maribyrnong, Vic.: Materials Research Laboratory.

4. Andrew, R.C. and Weston, G.M. (1977).
   The effect of overheating on the toughness of low sulphur/ESR steels. *Journal of the Australian Institute of Metals*, **21**, p. 126.

5. Burman, N.M. and Walsh, B.E. (1978).
   An alternative technique for maximum recovery fragmentation testing (MRL Report MD 78/1). Maribyrnong, Vic.: Materials Research Laboratory.

6. Zipp, R.D. (1979).
   Preservation and cleaning of fractures for fractography. SEM Inc., (Ed.) A.M.F. O'Hare, IL 60666, USA. Vol. 1, p. 355.

7. Andrew, R.C. and Weston, G.M. (1977).
   The effect of the interaction between overheating and tempering temperature on the notch toughness of two low sulphur steel. *Journal of the Australian Institute of Metals*, **22**, 200.

8. Bedford, A.J. and Walsh, B.E. (1980).
   Scatter in fragment mass/number distribution from nominally identical fragmentation tests (MRL Technical Note MRL-TN-447). Maribyrnong, Vic.: Materials Research Laboratory.

9. *Fracture mechanisms in naturally fragmenting materials.*
   Final Report on a Co-operation Research and Development Project between the Australian Department of Defence and the United States Department of the Army, Report MOU/FM/1/75, October 1975.

10. Lamborn, I.R. (1970).
The natural fracture and fragmentation of internally detonated steel cylinders: The influence of microstructure and mechanical properties (Defence Standards Laboratories Report 341). Maribyrnong, Vic.: Materials Research Laboratory.

11. Bedford, A.J. (1972).
The natural fragmentation of steel cylinders with tempered martensite microstructures (Defence Standards Laboratories Report 532). Maribyrnong, Vic.: Materials Research Laboratory.

SECURITY CLASSIFICATION OF THIS PAGE **UNCLASSIFIED**

DOCUMENT CONTROL DATA SHEET

REPORT NO.	AR NO.	REPORT SECURITY CLASSIFICATION
MRL-TR-91-36	AR-006-829	Unclassified

TITLE

The influence of grain boundary fracture on fragmentation behaviour — Part 2

AUTHOR(S)
George M. Weston and
Norbert M. Burman

CORPORATE AUTHOR
Materials Research Laboratory
PO Box 50
Ascot Vale Victoria 3032

REPORT DATE	TASK NO.	SPONSOR
October, 1991	DST 90/146	DSTO
FILE NO.	REFERENCES	PAGES
G6/4/8-4021	11	18

CLASSIFICATION/LIMITATION REVIEW DATE

CLASSIFICATION/RELEASE AUTHORITY
Chief, Materials Division

SECONDARY DISTRIBUTION

Approved for public release

ANNOUNCEMENT

Announcement of this report is unlimited

KEYWORDS

Sulphide precipitation Low alloy steel Payman

ABSTRACT

The effect of grain boundary sulphide precipitation on fragmentation performance has been investigated for low alloy steel cylinders tempered at selected temperatures within the range 150°C to 550°C. It was found that, as expected, increased cylinder hardness generally increased the fineness of cylinder fragmentation for both specially heat-treated cylinders with sulphide precipitates present at grain boundaries, as well as standard untreated cylinders. Over the range of tempering temperatures used, the specially treated cylinders, however, showed generally finer fragmentation as measured by a 15% to 30% increase in the Length Normalized Payman Fragmentation Parameter measured for these cylinders. Both fractographic and metallographic evidence indicated that the presence of grain boundary sulphide precipitation assisted in cylinder breakup for steel of the type tested.