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Effect of Insensitive HE on Shaped Charge Jets

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Abstract

Two different trends can be observed in the warhead community: on the one hand the demand for increased insensitive munition (IM) is still growing. This finally led to the replacement of TNT-bonded charges by plastic bonded ones (PBX). Contrary to TNT, a standard (inert) plastic binder cannot react within the very short times of a detonation front and thus leads to an increased roughness of the detonation front. On the other hand, there is also a demand for an increased performance of shaped charges with 10 calibers depth of penetration for Cu liners or even 12 calibers for Mo liners. This requires thin and usually not constant wall thickness liners. The possible conflicts of these two objectives were investigated in experimental studies, which are summarized in the present work.

1 Introduction

A few decades ago, shaped charges were typically filled with TNT-bonded explosives. Already at that time, it was tried to measure the roughness of the detonation front resulting from the inhomogeneity of the explosive ([1] & [2]) and the question was raised if this roughness has an impact on the performance of a shaped charge jet (SCJ). However, experiments showed that the influence was only marginal (e.g. [2] & [3]) and only little further attention was given to the topic.

The question re-emerged when the classical TNT bonded explosives were replaced by plastic bonded explosives (PBX) to make the charges more insensitive [4]. While the TNT binder was detonable and the detonation front could propagate with approximately the same velocity in the explosive and in the binder, this is not the case with the inert plastic binder. Consequently, the use of PBX increases the roughness of the detonation front.

At the same time, the developers of shape charges are striving for higher performance by the application of higher density liner materials and / or non-constant thickness liners – both measures at least partly decreasing the liner thickness and thus making the shaped charges (theoretically) more sensitive towards a rough detonation front. Facing these trends, the detonation front roughness became an issue again and an experimental program was launched to investigate its effects on the liner material and to quantify its influence on a shaped charge jet.

2 High Explosive Types

Three batches of the TDW PBX KS32 (HMX/HTPB 85/15, $\rho = 1.64\ g/cm^3$) with different HMX grain size distributions were manufactured:

- Standard: bimodal with mean grain sizes of 30 µm (fine mode) and 500 µm (coarse mode),

- Coarse: unimodal with mean grain size of 500 µm,
- Fine: unimodal with mean grain size of 30 µm.

With these three different KS32 batches both the roughness of the detonation front and the influence of this roughness on the SCJ behavior should be measured in the following two test series.

3 Roughness of a Detonation Front

In [1] and [2] the roughness of the detonation front was measured optically with a rotating mirror camera in streak mode. In [5], the authors studied shock wave interactions in multi point initiation systems by direct measurements of indentations in Oxygen Free High Conductivity (OFHC) copper, which is also used for SC liners. This technique was applied in this work as well. The principle of the test setup is sketched in Figure 1. The different KS32 types were initiated by a detonator and a Hexogen/Wax/Carbon (HWC) booster. An additional HWC disk of 10 mm thickness should ensure a safe initiation for all three KS32 types. The Cu plate below was used to witness the roughness of the detonation front. A final big steel block was added to trap the shock waves (avoiding reflections) and to stabilize the setup. The idea was to “print” the structure of the detonation front onto the Cu plate surface without significant lateral motion of this surface after the passage of the detonation front wave.

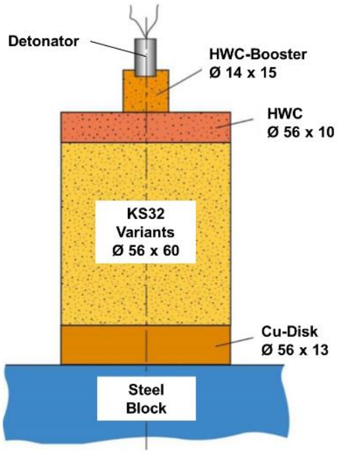

Fig. 1: Sketch of the test setup to measure a rough detonation front with a Cu witness disk.

To achieve these objectives three different configurations were investigated in numerical simulations. The models for these setups are shown in Figure 2. In the first configuration on the left side, a model as shown in Figure 1 was used. In the second configuration in the middle of Figure 2, the radial extension of the Cu witness plate was increased to avoid lateral movements of the Cu surface. In the third and final configuration on the right side, the Cu plate and a part of the KS32 were placed into a 20 mm deep milled hole in the steel block to largely avoid any radial movement of the Cu surface.

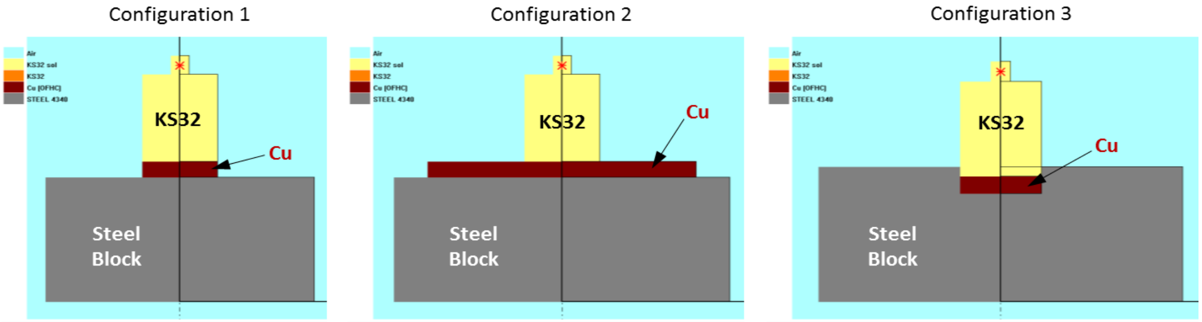

Fig. 2: Numerical simulation models for the three different configurations.

The numerical simulation studies clearly showed too large lateral flow of the copper in configuration 1, while the lateral movements of the Cu surface were already limited to between 2 – 8 mm (middle to edge) in configuration 2. The best results were achieved with configuration 3 with only 1 – 3 mm (middle to edge) radial shift of the Cu surface. Tests with all three configurations were conducted but with the focus on configuration 3.

3.1 Cast on Cu Disk

In a first test series the three types of explosives were cast onto extended and confined copper plates and detonated. The sample deformations were in close agreement with the predictions obtained from the numerical simulations. Figure 3 shows configuration 2 & 3 after the test, where in #3 the shock loaded Cu disk was already taken out of the setup.

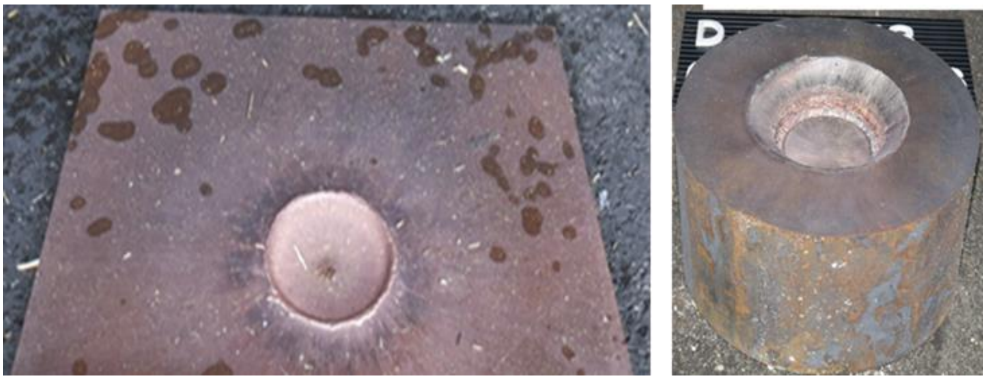

Fig. 3: Cu witness plate of configuration 2 (left) and steel block of configuration 3 without Cu sample (right) after the firings.

For each sample, the roughness of the copper surface, i.e. the indentations caused by the detonation front, was evaluated visually (optical microscopy) as well as by roughness measurement. Finally, the results of the different HE batches were compared to each other.

Typical results of the microscopic evaluation of the Cu surfaces are shown in Figure 4, where the roughness achieved with KS32-fine (left) and KS32-coarse (right) are highlighted. The difference between the two batches can already clearly be seen. The roughness of the fine grain sample is relatively low and partially even below the sensitivity of the meter, whereas the roughness measurement of the coarse grain sample yields maxima of 50 – 70 µm and 5 – 10 µm average. In Section 4, an SC liner with a thickness of 0.4 mm (400 µm) will be presented. The max. roughness could thus reach up to 10 – 15 % of the liner thickness.

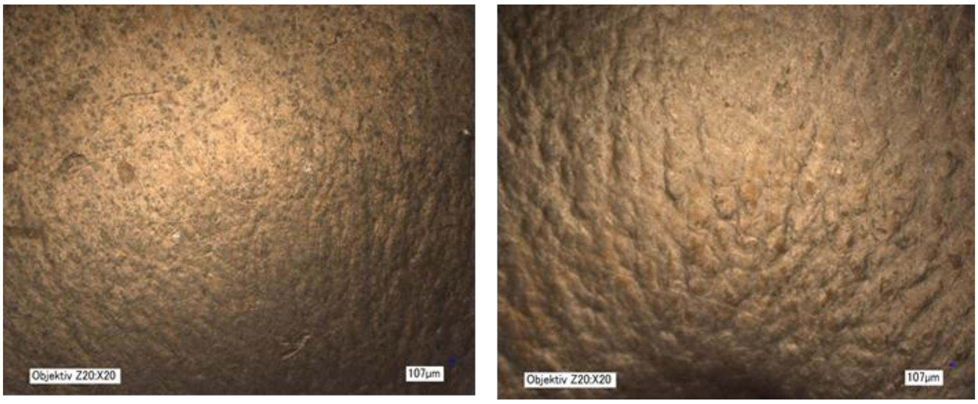

Fig. 4: Microscopic evaluation of the Cu surface roughness with KS32-fine (left) and with KS32-coarse (right).

3.2 Machined and glued on Cu Disk

The standard process for manufacturing shaped charges is casting the HE onto the SC liner. But sometimes, in more special cases, the HE is machined to fit onto a ready SC liner. Therefore, a second test series in configuration 3 was conducted with the KS32 explosive surface machined and then glued onto the Cu disk. Figure 5 shows in a series of pictures illustrating the surprising results – here exemplarily depicted for the KS32-standard. The left picture shows a micrograph of the machined, polished and further prepared surface of the KS32 sample. The yellow colored HMX-grains were thereby cut in a statistical manner. The corresponding test result is presented in the in the middle picture. The evaluation with an optical microscope shows many deep craters with diameters comparable to the cut HMX grain size distribution. Finally, a scanning electron microscope (SEM) picture of some of the craters is shown on the right. It was found that the crater depths are in roughly the same order of magnitude as the grain diameters.

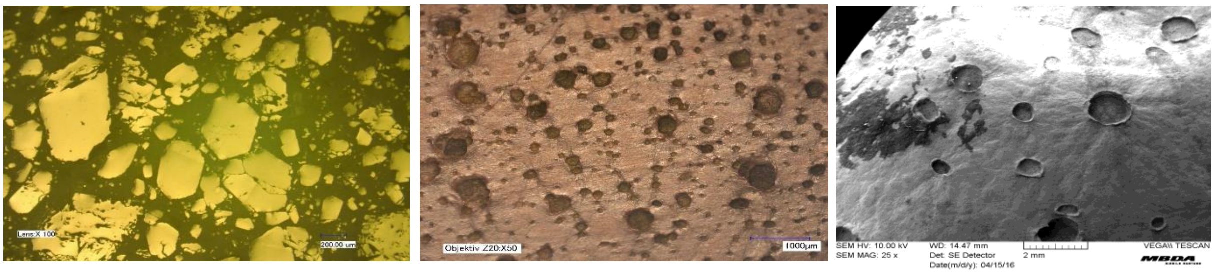

Fig. 5: Micrograph of cut and polished KS32-standard surface (left, HMX grains in yellow), Cu surface with craters after firing (middle) and SEM close-up picture of some craters (right).

From these results it must be concluded that machining the HE is not an appropriate process when thin high-performance SC liners are involved. Consequently, no further trials applying this technique were performed.

4 Influence of Roughness on the SC Jet

Based on the results obtained with the Cu surface roughness trials SC tests with the three KS32 types were planned. In a first step, an appropriate SC charge had to be designed. Thereby, several design requirements should be met:

- High tip-velocity were thought to be reasonable to achieve differences in the results,
- Thick enough SC jet to obtain an accuracy level high enough to see these differences,
- Simple and cost-effective design without detonation wave shaper
- Availability of the equipment to manufacture the SC selected liners

In numbers, the tip velocity should be as high as possible but not higher than 10.000 m/s (to keep it in a stable region) and the SCJ diameter should be at least 1.5 mm to ensure an accurate evaluation. Having these requirements in mind several SC liner designs were simulated and finally down-selected. In a second step, the candidate design of the shaped charge was then manufactured and filled with the three different KS32 types.

4.1 SC Design based on Numerical Simulations

Several SC designs and liners were taken into account and studied by numerical simulations for their usability in the planned test campaigns. The following parameters were varied:

- SC caliber: 44 mm and 64 mm
- Liner angle: 50°, 55° and 60°

- Liner wall thickness depending on liner angle

In total 12 simulations were performed and assessed by mainly analyzing the different mass profiles of the jets. Figure 6 exemplarily shows results with a caliber of 64 mm, liner angles of 50° and 60° and various liner thicknesses. The corresponding mass profiles are presented in Figure 7. In summary, tip velocities > 8000 m/s could only be reached with 50° liner angle for both calibers, but the required jet diameter could only safely be achieved with 64 mm caliber.

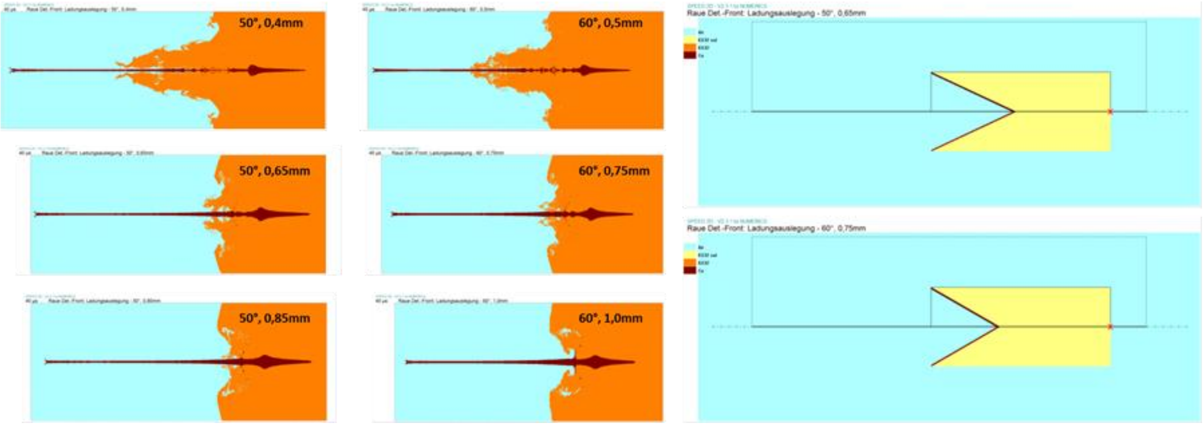

Fig. 6: Simulation model (right) and results (left) for a SC charge with caliber of 64 mm at t = 50 µs.

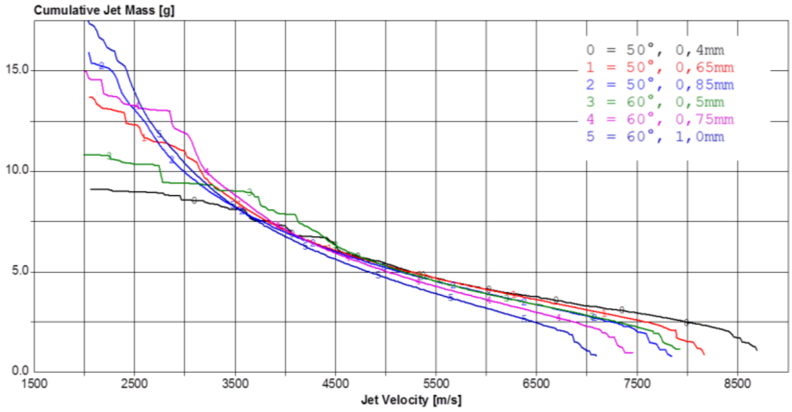

Fig 7: Mass profiles for the SC jets at t = 50 µs.

4.2 Selected SC Design

Following the simulation results and the underlying requirements, the SC design shown in Figure 8 was selected and manufactured. All three KS32 types were cast onto the liner and an additional HWC disk diameter 64 mm and thickness 10 mm (as introduced in Section 3) was applied to guarantee the same initiation conditions (run distances to detonation) for all three KS32 types. The explosive train was the same as in the roughness measurement test setup of section 3.

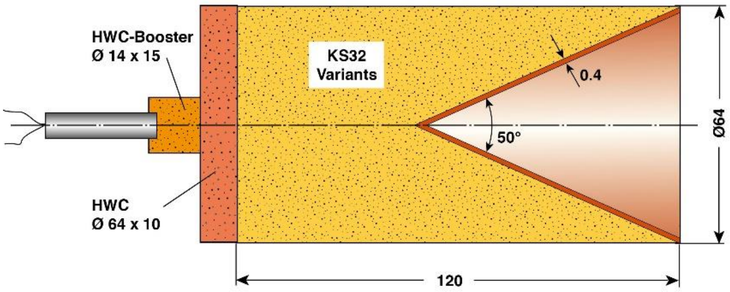

Fig. 8: Sketch of the test SC with a caliber of 64 mm.

The charges were fired in front of a double flash X-ray (FXR) camera and evaluated with respect to tip velocity, jet breakup, jet length and particle drift allowing a quantitative comparison of the influence of the grain size distribution and the detonation front roughness, respectively. Figure 9 shows a typical FXR picture with the nominal trigger times of t_1 = 160 µs and t_2 = 230 µs. Supplementary a reference Cu wire was added to the setup for a better assessment of the jet thickness.

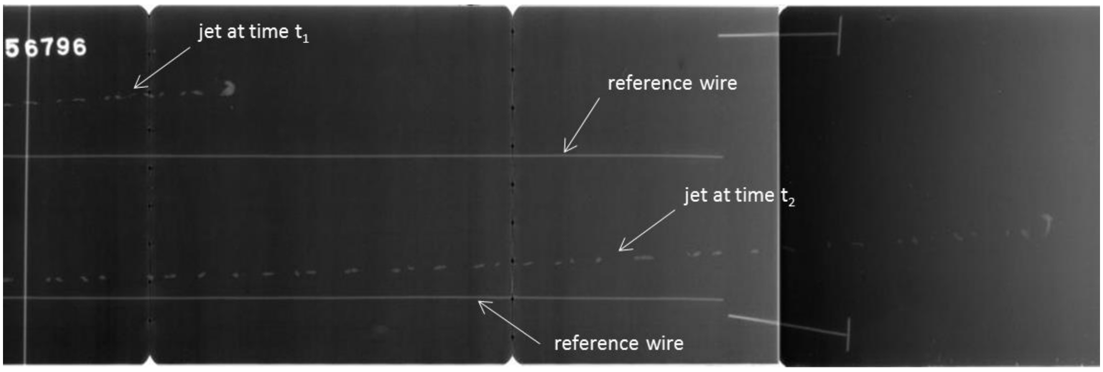

Fig. 9: FXR picture of the SC-Jet at two different times with a reference copper wire (HL56796).

4.3 Achieved SC-Jets and Evaluation procedure

In total, nine tests were conducted with the SC test charge containing the three different KS32 types (twofold repetition of each trial). Table 1 summarizes the test campaign showing the test numbering.

Tab 1: Summary of conducted SCJ test campaign

HMX grain size	standard	coarse	fine
series 1	HL56794	HL56795	HL56796
series 2	HL56797	HL56798	HL56799
series 3	HL56800	HL56801	HL56802

Figure 10 shows three FXR pictures of the tip (right) and rear part (left) of the SC jets with the three different KS32 types. Prior to the actual evaluation process these pictures shall be visually inspected.

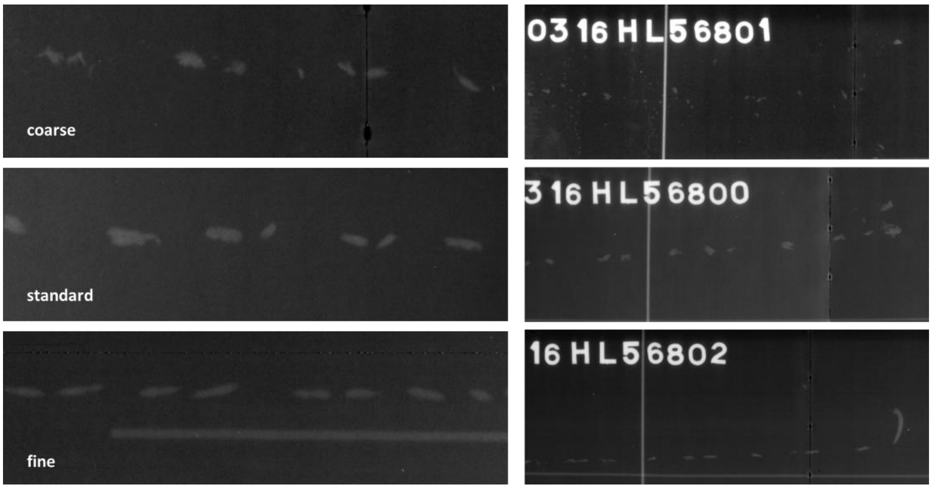

Fig. 10: Particulated SC jets: front part (right) and rear part (left) for the different KS32 types

The qualitative influence of the different the HMX grain sizes on the particles can be clearly seen in both parts of the jet: with KS32-fine the SCJ breaks up into well-defined particles, whereas with KS32-coarse these “particles” appear more like small fragments. With KS32-standard the behavior is somewhere in between.

All FXR pictures were electronically evaluated applying our in-house software EDI (Edge Detection in Images) [6]. EDI automatically detects the edges of the individual particles at the two FXR exposure times and determines tip velocity, jet breakup, jet length and particle drift. This data then allowed a quantitative assessment of the influence of the grains size distribution and thus of the roughness of the detonation front on these parameters. As an example for the EDI evaluation, Figure 11 shows a close-up of a part of a jet evaluation in an FXR picture for both tracks. Additionally, this detail highlights another aspect. From the comparison of the marked particle at t_1 and t_2, it can be concluded that the particles are spinning around their axes and that they are not always rotationally symmetric but are often flattened.

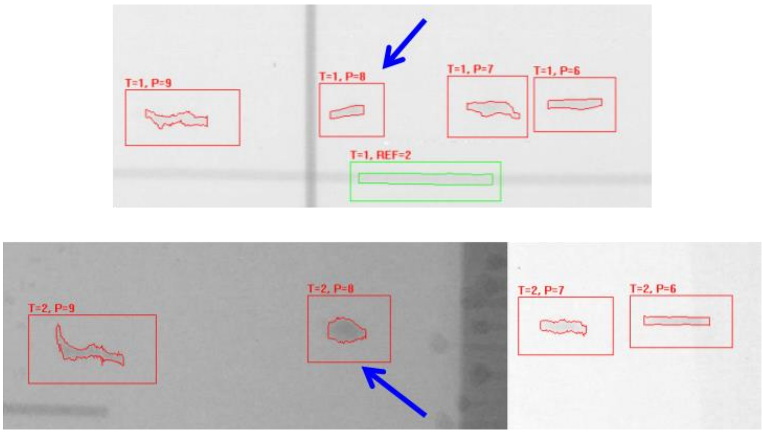

Fig. 11: Typical close-up of an EDI evaluation with a flat rotating particle (arrow).

4.4 Test Results

For the final quantitative assessment of the influence of the detonation front roughness on the SC jet behavior, all evaluation results were averaged over the three conducted trials per HMX grain size and compared to each other. This comparison is discussed in the following.

4.4.1 SCJ Velocity

Figure 12 shows the evaluation of the SCJ tip velocity for the three KS32 types (fine, standard and coarse. The open symbols indicate the three individual results of the trials whereas the full ones mark the mean values. All in all, the figure makes clear that no influence of the grains size on the tip velocity can be ascertained.

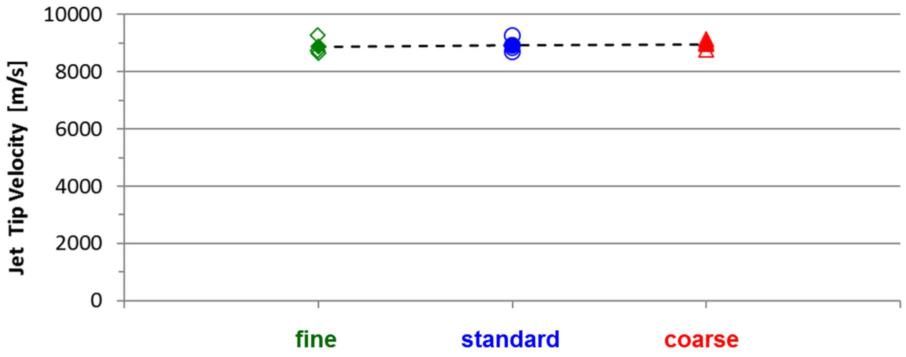

Fig. 12: Individual (open symbols) and averaged (closed symbols) SCJ tip velocities

4.4.2 Time and Position of SCJ Particulation

Figure 13 and Figure 14 illustrate the evaluation of all SCJ particles with respect to time and position of particulation. The assessment of mean breakup times in Figure 13 resulted in 78 µs for the fine, 64 µs for the standard and 62 µs for the coarse grained KS32 type with a standard deviation of ca. 22 µs. Due the nearly identical jet velocities, the comparison of the particulation positions in Figure 14 shows practically the same behavior with 514 mm, 415 mm and 395 mm, respectively.

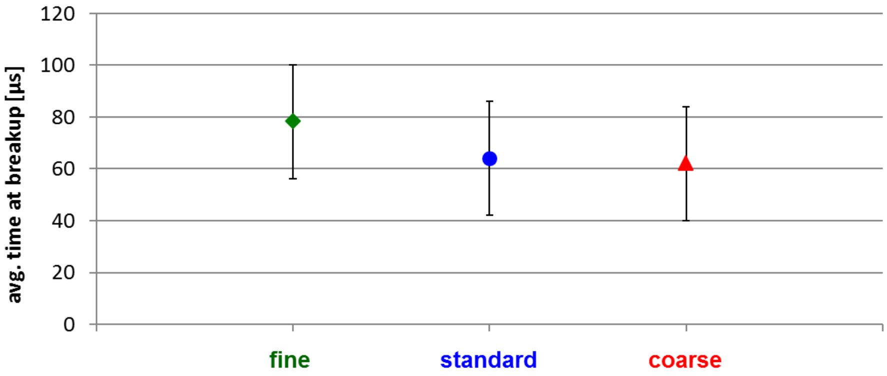

Fig. 13: Test results for the averaged particulation times.

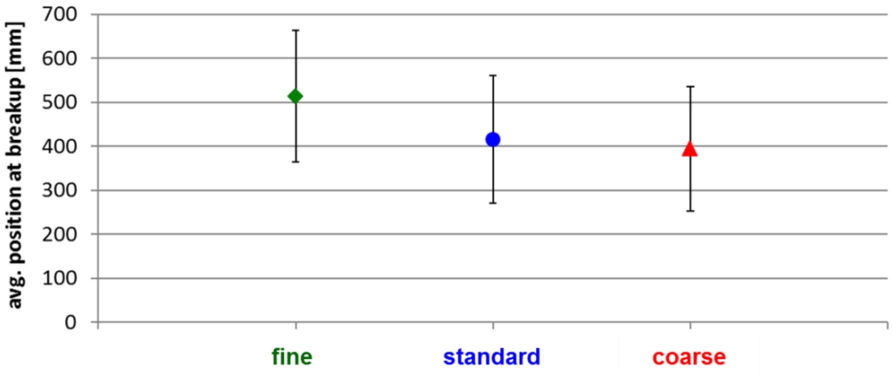

Fig. 14: Test results for the averaged particulation positions.

Even when the scattering in the data is taken into account, the tests clearly indicate that with the fine HMX grain size the particulation occurs at a larger distance and at a later time, respectively.

4.4.3 SCJ Cumulative Length

The cumulated length of the jet can be regarded as the most important parameter for the SCJ jet performance. The influence of the grain size distribution on this parameter is thus of particular importance.

Figure 15 shows the comparison of the averaged results. A significant influence of the grain size distribution on the jet length can be observed. Comparing the cumulated lengths at an exemplary jet velocity of 5000 m/s to KS32-fine, a 14% lower length can be observed with the KS32-standard charge and an even 18% lower length with the KS32-coarse charge.

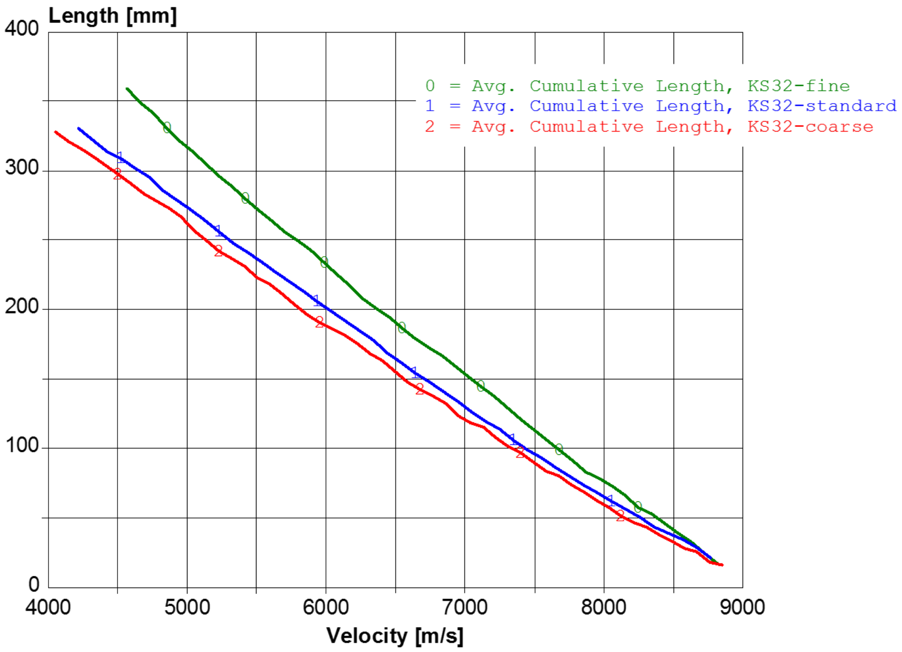

Fig. 15: Test results for the averaged cumulative jet lengths.

5 Conclusions

Three batches of KS32 (HMX/HTPB 85/15) with different distributions of the HMX grain size were manufactured:

- Standard: bimodal with mean grain sizes of 30 µm (fine mode) and 500 µm (coarse mode),
- Coarse: unimodal with mean grain size of 500 µm,
- Fine: unimodal with mean grain size of 30 µm.

With these three KS32 types test setups for the measurement of the roughness of the detonation front were developed. The roughness was directly measured by the indentation ("footprint") of the detonation front on Cu witness plates. In these tests with charges cast on the witness plates, a clear trend to an increased roughness with increased grain size could be observed. The roughest Cu surfaces showed maximum differences of 50 – 70 µm and 5 – 10 µm on average. It could further be found that the detonation front causes massive cratering in the CU surface, when the charge is machined and glued onto the Cu witness plates. This type of manufacturing process thus seems inappropriate for thin-walled SCJ liners.

Based on the results of this first study, a test shaped charge was designed to investigate the influence of this detonation front roughness on a shaped charge jet. In total nine SC charges were manufactured and shot in front of a FXR facility to study the particulated jets. An in-house software EDI was applied to evaluate and assess the SCJ characteristics. The SCJ velocity, particulation time and position and finally the cumulative length were evaluated. A significant influence of the roughness of the detonation front especially on the cumulative SCJ length was observed. At a jet velocity of 5000 m/s and compared to the KS32-fine charge, a 14% length decrease with KS32-standard and even 18% with KS32-coarse charge could be measured.

If the observed effects on the tested laboratory charge can also be found for practical (high-performance) shaped charges, however, is yet to be investigated. This will be part of future work.

Acknowledgement

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