Dry Ice Blasting to Increase Fatigue Strength

J. Hoffmeister[1], E. Schuch[1], M. Siedler[1] and T. Harter[1]

[1] Esslingen University, Faculty of Mechanical and Systems Engineering, Kanalstr. 33, 73728 Esslingen, Germany

Abstract
Dry ice blasting is a blasting process that is usually used to clean components. The main advantage of this process is the residue-free evaporation of the abrasive, so that the blasting material is not decontaminated. Another characteristic of the process is the low intensity. However, [1, 2] have already shown that the surface condition of components can be changed by dry ice blasting. In this paper, therefore, dry ice will be used specifically to harden material specimens. Two materials are used: a soft aluminum alloy EN AW-5754 and a soft annealed tool steel 90MnCrV8. Subsequently, the surface condition in terms of roughness, residual stresses and strain hardening was investigated and the cyclic properties of the specimens were determined.

Keywords: dry ice blasting, fatigue strength, residual stresses

Introduction

Dry ice blasting, also called dry ice cleaning, is a compressed air blasting process that uses dry ice at a temperature of -78.5 °C as blasting medium. Basically there are two advantages of the process: on the one hand, even sensitive workpieces can be treated with little damage due to the low hardness of the blasting medium and, on the other hand, dry ice evaporates after blasting, so that it is no longer necessary to clean the workpiece of the blasting medium. No other blasting process has this advantage [3].

Three respectively four effects play a role in the dry ice blasting process: mechanical, thermal and sublimation effects and additionally a solvent effect is reported in some cases [4]. In order to quantify the different effects on decoating processes, [5] has investigated and determined the effective proportions of the several effects with the aid of various experiments. Among others, in order to quantify the mechanical effect of dry ice blasting, [3] measured the Almen intensity [6], which is a parameter primarily used in consolidation blasting. However, preliminary investigations have shown that it is not possible to measure the arc height with the Almen-“N” [7], which is used for shot peening with low beam intensities. Therefore, so-called Aero Almen strips "AA" [8] were used, which consist of an aluminum alloy A2024-T3 instead of a spring steel SAE1070. The Aero Almen strips also enabled to measure deflections of the Almen strip during dry ice blasting. Comparing different blasting processes, comparable Almen intensities could be determined with nutshell granules at lower pressures. Tests concerning the removal rate of ceramic thermal barrier coatings showed similar removal rates for both blasting media at comparable blasting intensities. The author concluded that the mechanical effect of dry ice blasting is high. At temperatures of the workpiece of 20 °C, the mechanical percentage was quantified by 85 % and the thermal percentage by 15 %. However, the ratios depend on the temperature of the workpiece; the thermal effect increases as the temperature of the workpiece grows. The proportion of the sublimation effect was not detectable.

With regard to the effect on the surface layer condition, it has already been shown by [1, 2] that dry ice blasting can influence both the hardening depth profiles and the residual stress condition. Also other processes with a low Almen intensity, such as micropeening have an influence on the surface condition and can also increase the fatigue strength significantly [9–11]. Based on the findings that even low intensities have an influence on the fatigue strength, and that dry ice blasting with even lower intensities can change the surface layer positively, this work shows the influence of dry ice blasting on the fatigue strength.

Experimental Methods

In this project two materials were used: a tool steel 90MnCrV8 [12] in the soft annealed condition and an aluminum alloy EN AW-5754 [13]. The allowable and measured chemical composition of the two materials are shown in table 1: for the tool steel and in table 2 for the aluminum alloy. Both materials do not show any deviations from the standards.

table 1: Specification of the chemical analysis according to the standard [12] and the measured chemical analysis for 90MnCrV8

elements	C	Si	Mn	P	S	Cr	V	Mo	Fe
according standard in mass-%	0,85-0,95	0,1-0,4	1,8 - 2,1	max. 0,03	max. 0,03	0,2-0,5	0,05-0,2	-	rest
chemical analysis in mass-%	0,85	0,284	1,99	$<5\cdot10^{-4}$	$<5\cdot10^{-4}$	0,445	0,111	0,18	rest

table 2: Specification of the chemical analysis according to the standard [13] and the measured chemical analysis for EN AW-5754

elements	Si	Fe	Cu	Mn	Mg	Cr	Zn	others	Al
according standard in mass-%	max. 0,4	max. 0,4	max. 0,1	max. 0,5	2,6 - 3,6	max. 0,3	max. 0,2	max. 0,15	rest
chemical analysis in mass-%	0,173	0,304	0,028	0,267	2,92	0,034	0,039	0,15	rest

Bored flat specimens were manufactured from sheet metal by laser cutting. This results in a notch factor of K_t = 2.5. The area of the notches was manually treated by dry ice blasting. For comparison purposes, some of the aluminum specimens were also manually sand blasted (compare figure 1). None of both surface treatments was optimized.

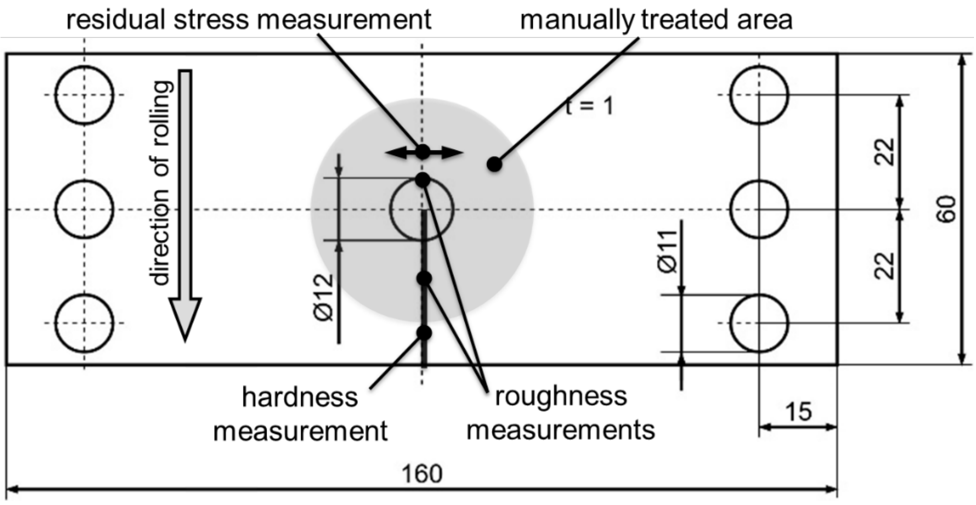

figure 1: Geometry of the notched flat specimens, illustration of the manually mechanical treated area and the measurement direction

The surface conditions of the specimens were characterized. All measurement point are illustrated in figure 1. The hardness distributions in the cross section trough the notch and the roughness in the base of the notch were measured. Additionally the residual stresses near the notch were measured by X-ray diffraction. The measurement conditions and basis for the calculation of the residual stresses are listed in table 3 for the investigated materials. For the evaluation of the residual stresses the cosα-method was used. The complete depth distributions of residual stresses were measured by alternating electro polishing and measuring steps. Because of the fact that the removed area was small, the stress relaxation was ignored.

table 3: basis for the calculation of the residual stresses

	90MnCrV8	EN AW-5754
Interference line	{211}	{311}
Radiation	Cr-Kα	Cr-Kα
Young's Modulus of the interference line $E^{\{\}}$	224.00 GPa	69.31 GPA
Poisson ratio of the interference line $\nu^{\{\}}$	0.28	0.348
Stress free diffraction angle $2\theta_0$	156.396 °	139,497 °

With both materials five tensile tests were performed. Finally, all specimen conditions and materials were cyclic loaded with a stress ratio $R = -1$ and the cyclic test results were statistically evaluated. In the long-life fatigue region, at least 12 specimens per surface condition were tested. The results were evaluated with the staircase method according Hück [14]. A test was finished as soon as the specimen was broken or the ultimate number of load cycles of 10^7 was achieved. In the high cycle fatigue region, the tests were evaluated according to the method of discrete load steps [15].

Experimental Results

The tool steel was changed significantly by the thermal influence of the laser cutting. This resulted in a martensitic zone in the laser-machined areas. This zone can be seen in the hardness distribution (see figure 2 left). The laser cutting changed the hardness from approximately 200 HV 0.1 of the soft annealed initial condition to approximately 600 HV 0.1 near the laser cut area. After dry ice blasting the hardness of the tool steel was not affected. The difference between the untreated and the dry ice blasted condition near the surface can be attributed to measurement inaccuracies or could be the result of the martensitic layer, which is not formed uniformly.
For the aluminum alloy (compare figure 2 right), the surface hardness increased slightly to bore from approximately 78 HV 0.1 to 88 HV 0.1. This can be related to laser cutting. There are no differences in hardness distribution between the three conditions.

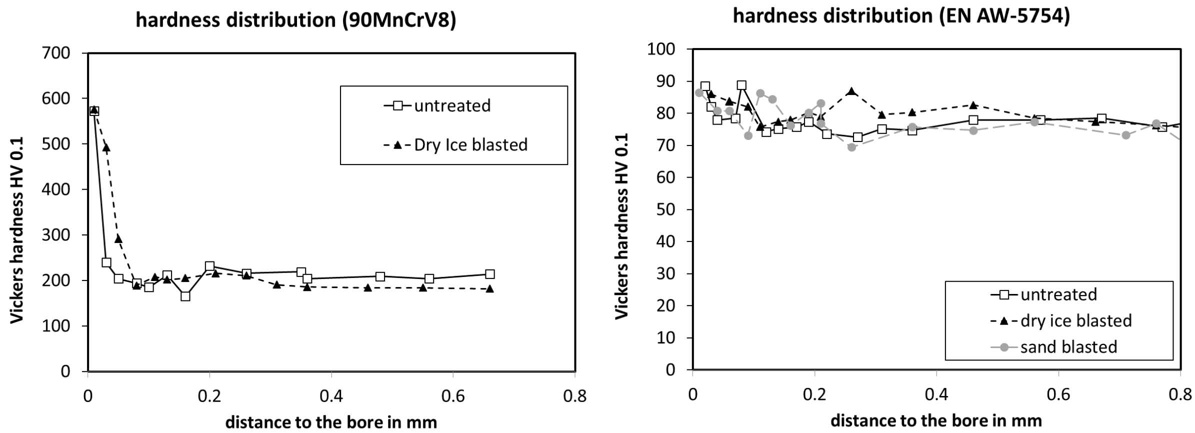

figure 2: Hardness distribution for 90MnCrV8 (left) and EN AW-5754 (right)

Due to the fabrication of the bored flat specimen by laser cutting a relatively high roughness is resulting in the Ø12 bore (notch). For the tool steel 90MnCrV8, the average roughness of the untreated condition in the bore was *R*z = 11.7 µm. After dry ice blasting, the average roughness *R*z = 13.4 µm was determined. When the scatter of the roughness measurement is taken into account, it can be stated that in the bore no changes were produced as a result of dry ice blasting. Additional roughness measurements in the area close to the bore on the plane showed an average roughness for the untreated condition of *R*z = 8.6 µm and for the dry ice blasted condition of *R*z = 2.7 µm. Here, an improvement is visible due to the dry ice blasting. For the aluminum alloy, an average roughness for the untreated condition of

Rz = 40.3 µm, for the dry ice blasted condition of Rz = 37.3 µm and for the sand blasted condition of Rz = 27.7 µm was measured in the bore. Once more, taking into account the scatter of the measurement, the roughness was not changed by dry ice blasting. Sand blasting slightly improved the roughness in the area of the bore. In addition, an edge rounding in the area of the bore could be detected due to sand blasting. Considering the roughness in the area of the bore on the planes, an average roughness Rz = 0.75 was measured for the untreated condition, Rz = 2.8 µm for the dry ice blasted condition and Rz = 37.5 µm for the sand blasted condition. The roughness of the aluminum alloy in the area of the bore was slightly degraded by dry ice blasting and massively degraded by sand blasting.

The residual stresses and full width at half maximum distribution (*FWHM*) for the two materials and the different surface layer conditions are shown in figure 3. For the tool steel 90MnCrV8 (figure 3 left), it can be seen that the untreated initial state already contains residual compressive stresses. These residual compressive stresses could be slightly increased by dry ice treatment. Unfortunately, it is not possible to make any clear statements about the depth, since the electrolytic ablation was no longer uniform starting from an ablation depth of approx. 40 µm on. This nonuniformity had an influence on the measurement results. The full width at half maximum distribution was not influenced by the dry ice blasting, so that probably no work hardening was induced.

The residual stresses of the aluminum alloy EN AW-5754 could be influenced more significantly by both mechanical surface treatments. The untreated condition shows low compressive residual stresses near the surface, which disappear relatively quickly with the depth. The dry ice blasted condition shows the highest surface residual compressive stresses of approximately σ^{rs} = -115 MPa at the surface. These compressive residual stresses decrease with the depth. The sand blasted condition also shows compressive residual stresses, but less compared to the dry ice blasted condition: σ^{rs} = -60 MPa. At depth, compressive residual stresses still build up. From a depth of approximately 20 µm, the residual stresses are similar for both treated conditions. However, the zero crossing of the residual stresses could not be measured, which is due to the electrolytic removal in interaction with the thin flat specimens. The removal causes the residual stresses to be redistributed, which leads to incorrect measurement results. Still, the depth effect of the blasting treatment can be estimated from the full width at half maximum distribution. The untreated condition shows approximately a constant leveling of the full width at half maximum values over the depth. The dry ice blasted condition shows slightly increased values, which reach the level of the untreated condition by about 60 µm. The sand blasted condition shows the highest full width at half maximum values at the surface. This initial value remain constant in the depth and drop from approximately 10 µm until they reach the values of the untreated condition at 160 µm. Sand blasting thus produces the greater work hardening effect than dry ice blasting, but dry ice blasting also work hardens the aluminum alloy.

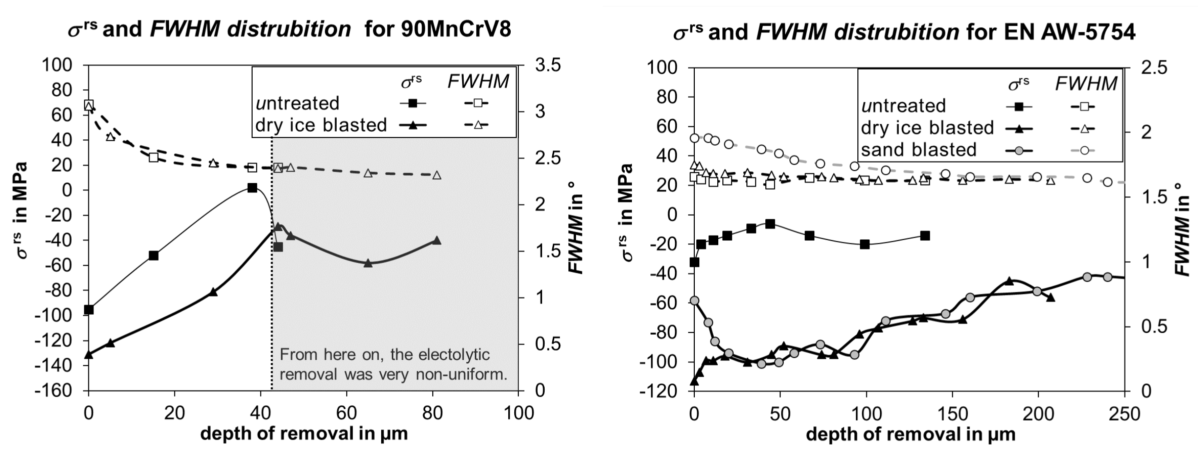

figure 3: Residual stresses σ^{rs} and full width at half maximum *FWHM* distribution near the bore for 90MnCrV8 (left) and EN AW-5754 (right) with different surface conditions

The results of the fatigue tests after the evaluation are illustrated in figure 4 and the resulting specific values are listed in table 4. Regarding the results of the tool steel 90MnCrV8 (see figure 4 left), the fatigue limit of the dry ice blasted tool steel could be increased slightly by 3 % for a failure probability of 50 % and by 6.5 % for a failure probability of 10 % compared to the untreated condition. The strength is therefore hardly influenced. Considering the scatter of cyclic test results, the increase can be neglected.
For the aluminum alloy EN-AW-5754 (figure 4 right), a significant increase of the fatigue limit was determined for both blasting processes. For the sand blasted condition, the fatigue limit was increased by 22.8 % for a failure probability of 50 % and 23.3 % for a failure probability of 10 % compared to the initial condition. The dry ice blasting process even achieved an increase of 28.9 % for a failure probability of 50 % and 30.5 % for a failure probability of 10 % compared to the initial condition. So it was possible to increase the fatigue limit by dry ice blasting more then by sand blasting, although the intensity of the dry ice blasting process is much lower.

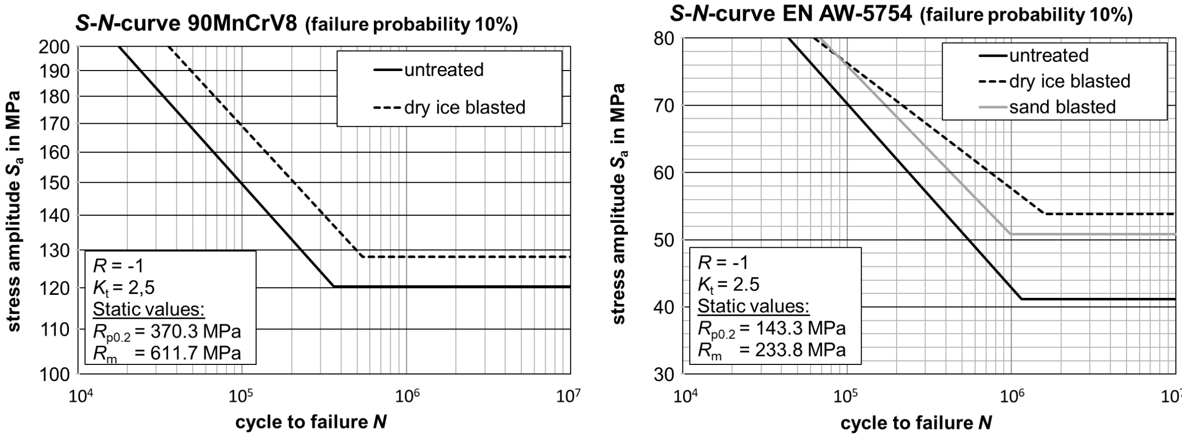

figure 4: *S*-*N*-curve with a failure probability of 10 % and a stress ratio R = -1 for bored flat specimens with a notch factor of K_t = 2.5 for 90MnCrV8 (left) and EN AW-5754 (right) with different surface conditions

table 4: summary of the statistic evaluation of the cyclic tests (*failure probability of 10 % or 50 %)

Material	**90MnCrV8**		**EN AW-5754**		
Surface condition	**un-treated**	**dry ice blasted**	**un-treated**	**dry ice blasted**	**sand blasted**
Fatigue limit $S_{F,10\,\%}$* in MPa	120.4	128.2	41.2	53.8	50.8
Fatigue limit $S_{F,50\,\%}$* in MPa	129.6	133.6	42.5	54.8	52.2
Edge load number of cycles N_D	361263	541212	115527	1592477	985305
***k*-factor (slope of the curve)**	5.93	6.11	4.92	8.13	5.86

Conclusion

It was shown that dry ice blasting can influence the surface condition of metallic materials positively. The roughness was not influenced by dry ice blasting for rough initial conditions. For low initial roughness, an improvement of the roughness was observed for the tool steel and a slight increase was measured for the aluminium alloy. The influence of dry ice blasting is also visible for the residual stresses. For the tool steel and for the aluminium alloy compressive residual stresses can be induced by the dry ice blasting. The hardening effect is clearly more obvious for the aluminium alloy than for the tool steel. The results of the cyclic investigations show that no change could be observed for the tool steel. However, this result is relativized when taking into account the increase in hardness in the peripheral area of the bore, which was caused by the laser cutting, and the high roughness. This combination

represents a difficult starting point for cyclic testing. For the aluminium alloy, a significant increase in fatigue strength was determined for the dry ice blasted condition. This is also illustrated by the additionally considered process of sand blasting, which achieves smaller increases in fatigue strength than the dry ice blasted condition.
In order to determine clearer limits of the dry blasting process in terms of the effect on different materials, even materials of higher strength, further investigations are necessary and in addition the process should be optimized for work hardening.

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