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HARDNESS AND MICROSTRUCTURE EFFECTS ON SAE 1045 STEEL WEAR

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Abstract. *Studying steel wear is extremely important to industry as the use of current tribology knowledge and technologies could generate significant savings worldwide. This work aims to evaluate the relationship between hardness, wear and microstructure of a tribological pair formed by SAE 1045 steel - quenched and normalized - and zirconium oxide, a high hardness material. For this purpose, the pair of materials was subjected to pin-on-disc wear tests. By means of microscopy and interferometry, the wear mechanisms were evaluated. Abrasion and adhesion mechanisms were observed at the end of the tests for all quenched and normalized samples. It was observed that the normalized discs presented lower hardness and higher wear, while the respective balls presented elliptical marks due to the lower hardness of the material.*

Keywords: *abrasion, adhesion, hardness, wear resistance.*

1. INTRODUCTION

According to Holmberg and Erdemir (2017), approximately 23% of all world energy consumption originates from tribological contacts. The authors predicted that, if the currently available surface treatments and materials technologies were applied in order to reduce friction and wear, energy losses could be reduced by 40% in a period of 15 years.

The tribological contact between metallic surfaces presents, according to classification reported by Zum Gahr (1987), wear mechanisms by adhesion, abrasion, surface fatigue and tribo-chemical reactions. Usually, wear at a specific condition is a mixture of these mechanisms, while metallurgical properties such as hardness, ductility and crystalline structure play a fundamental role in this process. Choices of alloy and heat treatment are the most usual ways to increase the tribological performance of steel components, with hardness usually being the controlled property. However, high hardness does not guarantee low wear since its influence depends on the active wear-mechanism. The same can be considered about microstructure.

This work aims to evaluate the influence of hardness and microstructure on the wear resistance of SAE 1045 steel subjected to different heat treatments. Specifically, the study aims to characterize microstructure of tested materials as well as evaluate wear and its mechanisms.

2. METHODOLOGY

Six 1045 steel discs with 15 mm thickness and 55 mm diameter went through the following heat treatments: quenching (discs 1A, 1B and 1C) and normalization (discs 2A, 2B and 2C). The counterparts in the pin-on-disc tests were zirconium oxide balls (ZrO_2) with 8 mm diameter. Figure 1 shows a disc after test and a ball.

Figure 1. Materials used in the tribometer tests.

The tests were performed in the tribometer from the Laboratory of Tribology, located at Federal University of Rio Grande do Sul, presented in Fig. 2. The data measured during the tests were used to calculate the friction through Eq. (1).

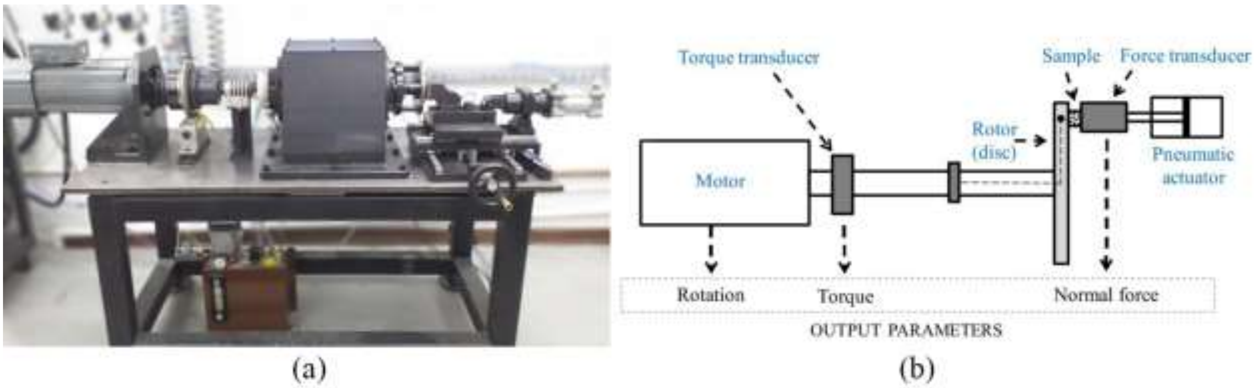


Figure 2. Tribometer used in wear tests: (a) photo and (b) schematic with sensors.

$$\mu = \frac{T}{Fr} \tag{1}$$

Where: T is the torque measured in the shaft [Nm], F is the normal force measured along the pneumatic actuator [N] and r is the effective radius where the force is applied [m].

Prior to each test, the discs were sanded to achieve roughness less than 0,8 µm (Ra) as specified by ASTM G99. Sandpaper grades 180, 240, 320, 600 and 1200 were used. Then disc surfaces and balls were cleaned with acetone to remove impurities. The average roughness (Ra) of the discs – evaluated with a Mitutoyo digital portable surface roughness tester model SJ-210 – was below to 0,1 µm.

The parameters used in the wear tests are presented in Tab. 1.

Table 1. Parameters used in the wear tests.

Radius	Force	Sliding speed	Sliding distance	Rotation	Time
18 mm	200 N	0,25 m/s	1800 m	133 rpm	7200 s

To analyze discs microstructures after heat treatments, discs 1A and 2A (quenched and normalized, respectively) were cut after testing and then samples were embedded, sanded, polished and attacked with Nital 2%.

Samples hardness were evaluated prior to the tests, adding up to six measurements per track. For this, an EMCO-TEST hardness equipment was used, model DuraVision 30 G5.

Wear mechanisms and microstructure were evaluated through a Zeiss optical microscope, model Axio Lab A1 and a stereo microscope Zeiss, model Stemi 508.

Discs worn volumes were measured by a Bruker interferometer, model CountourGT-K 3D. The wear tracks were evaluated in two distinct regions of the disc – approximately 180° apart from each other. Four two-dimensional profiles were obtained from each region using AxioVision SE64 software, adding up to eight profiles per track. Figure 3-a shows a region measured by interferometry and Fig. 3-b a two-dimensional profile. From the two-dimensional wear profiles, the worn volume (in mm³) were calculated using an algorithm developed in Matlab. This software uses the profile area and the track radius to determine the volume worn on the disc track.

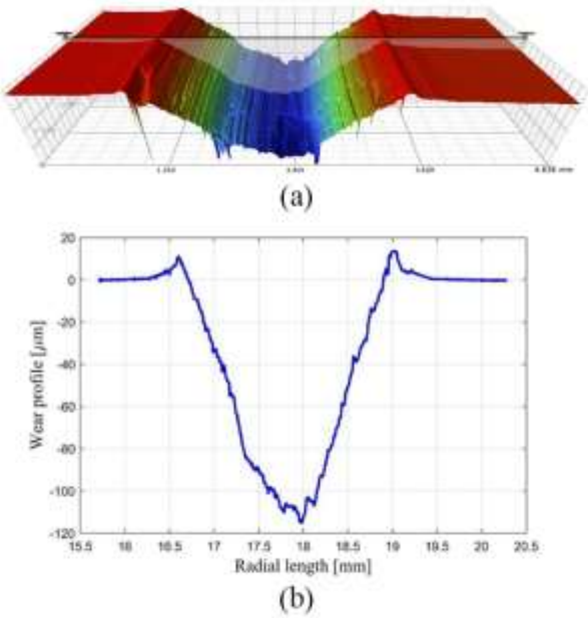


Figure 3. Example of a disc wear track interferometry: (a) three-dimensional track and (b) two-dimensional profile.

Balls worn volumes were calculated through the method proposed by ASTM G99, which is based on the circle radius defined by the wear marks. These radii were measured through images of the balls obtained with a Zeiss stereo microscope model Stemi 508 and ImageJ software.

3. RESULTS

3.1 Metallographic analysis

The microstructures resulting from the quenched discs, using disc 1A as sample, are presented in Fig. 4. The expected microstructure of SAE 1045 steel after quenching is martensite and/or tempering martensite. It is observed that there is martensite only in a surface layer of the disc, around 30 μm, where the cooling rate was sufficiently high. On the other hand, at the disc central region (Fig. 4-a), where the cooling rate was lower, perlite (arrow 1) and pro-eutectoid ferrite (arrow 2) were observed. This was due to SAE 1045 steel low hardenability, a characteristic that explains the requirement of high cooling rate to obtain the martensitic structure.

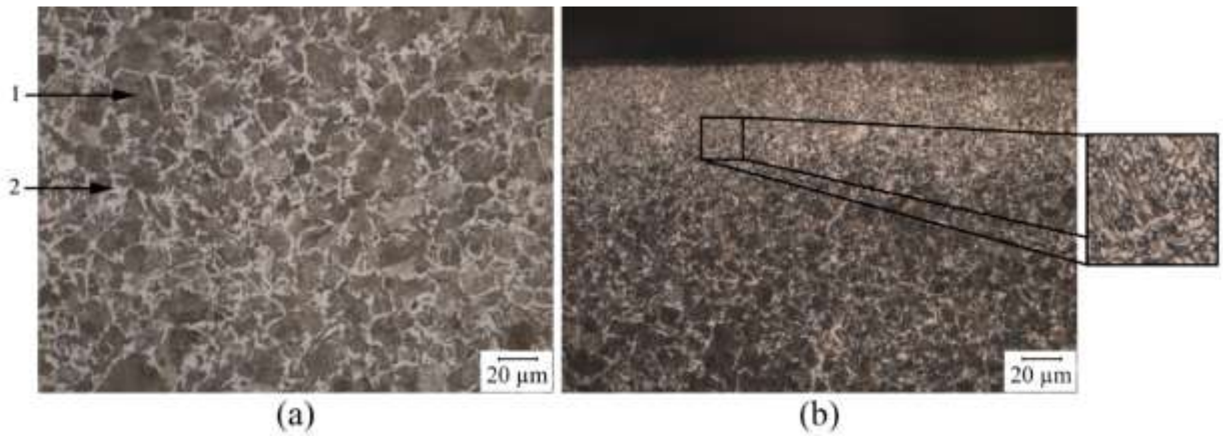


Figure 4. Quenched disc 1A microstructure: (a) in the disc central region and (b) close to the surface.

While quenched discs microstructure was not homogeneous, on normalized discs (Fig. 5) the presence of perlite (arrow 1) and pro-eutectoid ferrite (arrow 2) with refined grain (Fig. 5-a), expected for medium carbon steels with this treatment, is seen throughout the disc. Due to the lower cooling rate compared to the quenching treatment, there is a higher amount of ferrite in the normalized disc when compared to the quenched disc.

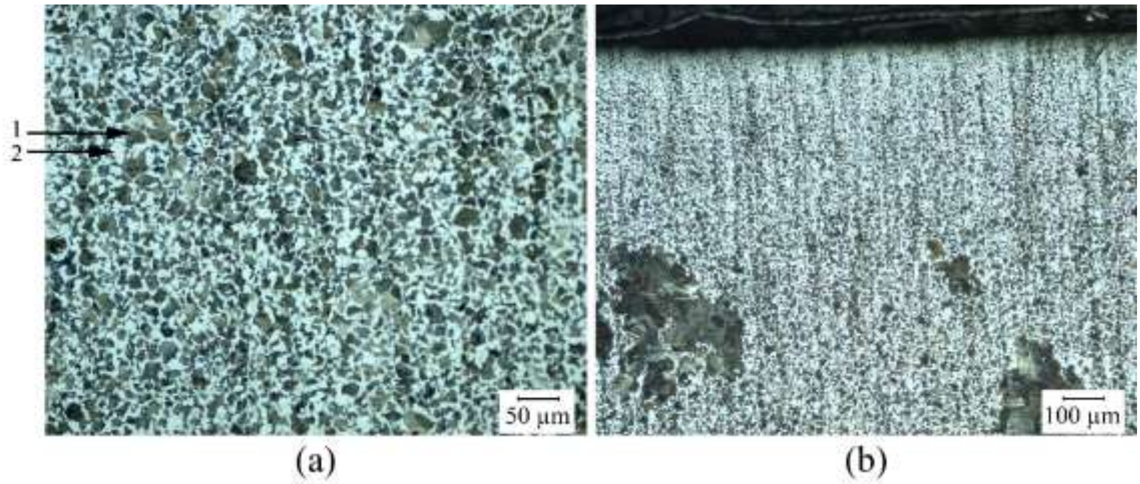


Figure 5. Normalized disc 2A microstructure: (a) in the disc central region and (b) close to the surface.

3.2 Hardness

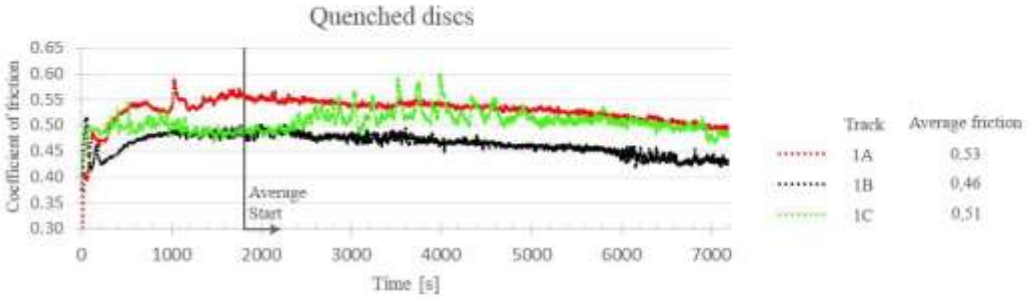
Table 2 shows six average hardness measured close to the tracks produced by the wear tests. The measurements were taken prior to the tests and the indentations were made along the track, but outside its path, so they would not interfere with wear results. The quenched discs average hardness was 286 HB, 50% higher than the normalized discs (191 HB). Quenched discs presented higher hardness due to the presence of martensite on the surface, while the normalized discs presented smaller hardness due to the microstructure of perlite and ferrite, as consequences of normalization.

Table 2. Average Brinell hardness.

	Track	**Average track [HB]**	**Average disc [HB]**
Quenched	1A	295 ± 10,2	286 ± 11.3
	1B	280 ± 4,8	
	1C	273 ± 2,7	
Normalized	2A	188 ± 5,3	191 ± 5.3
	2B	188 ± 4,6	
	2C	193 ± 5,0	

3.3 Friction

The friction curves measured during wear tests are shown in Fig. 6. In each test its average friction was considered after the first 30 minutes (1800 s) in order to exclude running effects from the analysis. The average value for each track is presented in the graph captions.



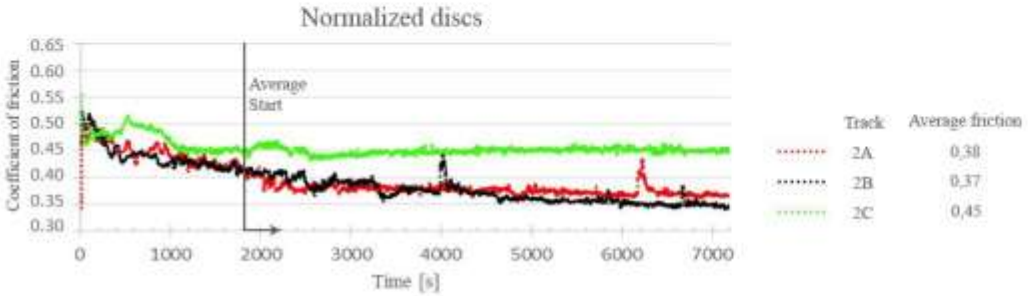


Figure 6. Friction curves in each test.

It is observed that discs from group 2 (normalized) had lower coefficients of friction when compared to discs from group 1 (quenched). This may be related to particular characteristics generated by the presence of perlite in the microstructure, in which cementite contained in the perlite is morphologically arranged as continuous plates, creating a continuous hard-phase support and favoring not only greater slippage but also reduction in friction. The friction results were evaluated through ANOVA statistical method, which indicated there are no significant difference between the values.

It is important to highlight that temperatures were not high enough to change discs microstructure and that an in-depth analysis of friction is not the purpose of this paper.

3.4 Worn volumes

Figure 7 shows, in a comparative way, the mean worn volumes for balls and discs.

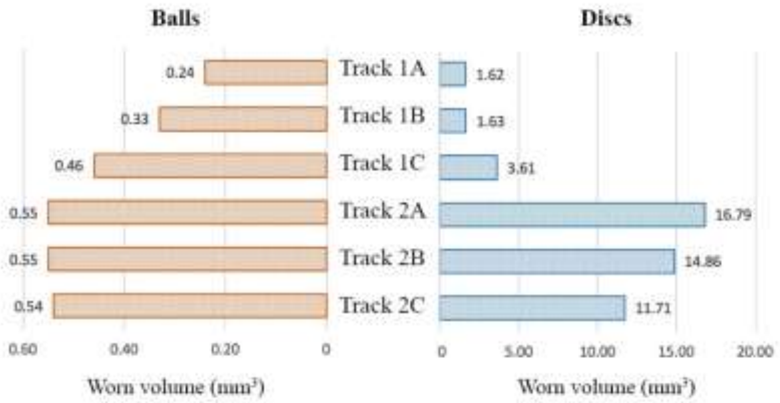


Figure 7. Mean worn volumes.

It can be observed that quenched discs wear was considerably lower than normalized discs wear, which agrees with the literature (Mutton and Watson, 1978, Xu et al., 2017), where it was reported that harder materials have higher wear resistance. Furthermore, these results agree with Archard equation, where hardness and wear behave inversely. The normalized discs average-wear was 14,5 mm^3, 6,2 times higher than that obtained from quenched discs (2,3 mm^3). The zirconium oxide balls tested against the quenched discs had an average wear of 0,34 mm^3 (15% of discs wear). The average wear of balls rubbed against the normalized disc was 0,55 mm^3 (4% of the discs wear).

3.5 Wear mechanisms

Microscopies from all worn tracks can be seen in Fig. 8.

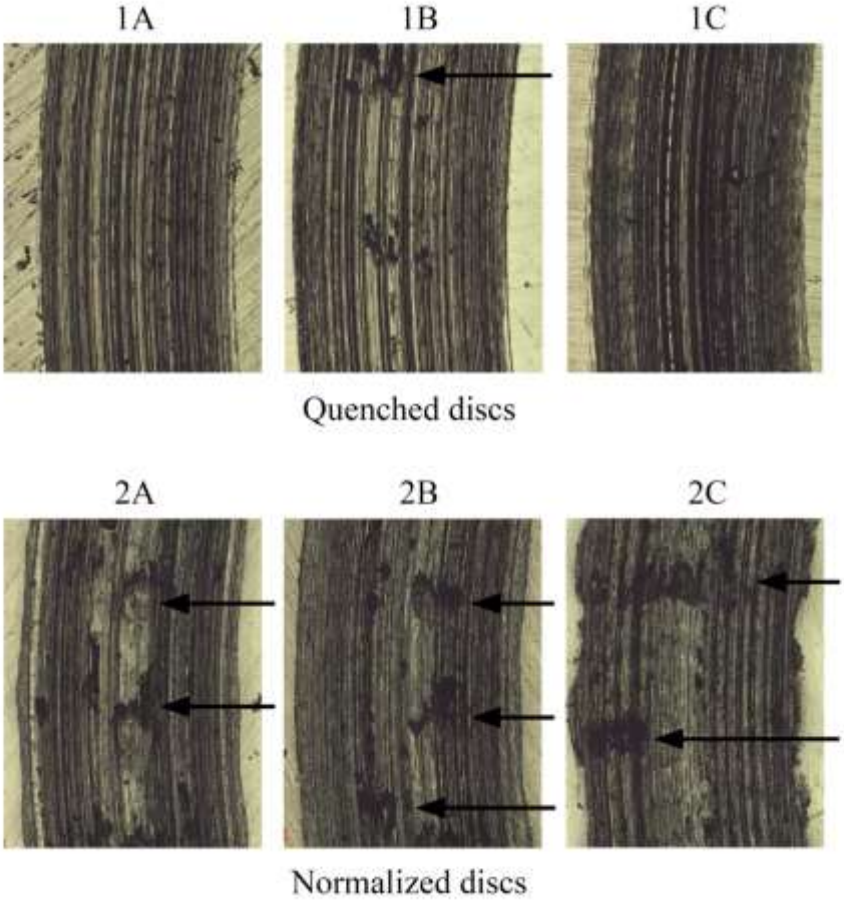


Figure 8. Microscopies of each disc: the arrows indicate adhesion marks.

Elongated grooves are seen in sliding direction in all the tracks, which come from the abrasive process with the zirconia ball. Another visible and indicated mechanism in Fig. 8 is the steel adhesion to the ball, which causes the material to be pulled out of the disc. A microscope analysis indicated that black marks were indeed a hole because they were deeper than wear track. According to Stachowiak and Batchelor 2006, adhesion between metals and ceramics can occur under some conditions, and most times it is related to chemical affinity, furthermore adhesion is characterized by high wear rates. This may explain why normalized discs, which suffered predominantly adhesion, showed higher wear than quenched discs.

Figure 9 shows the worn balls surfaces appearance and also the interferometry of a ball from each pair (quenched and normalized disc). It is observed that the balls used in the normalized discs shows marks in elliptical shape (Fig. 9-b), different from the balls used in the quenched discs, which are circular (Fig. 9-a). This effect is more evident in Fig. 9-c and Fig. 9-d. The circular marks present on the balls rubbed against quenched discs are due to a flat wear of the ball, whereas the elliptical mark corresponds to a greater wear on the center of the track. Another important aspect with regard to the wear mechanism is that the ball surface rubbed against the normalized disc has less prominent grooves, which favors the establishment of greater contact area with the disc and, consequently, adhesion.

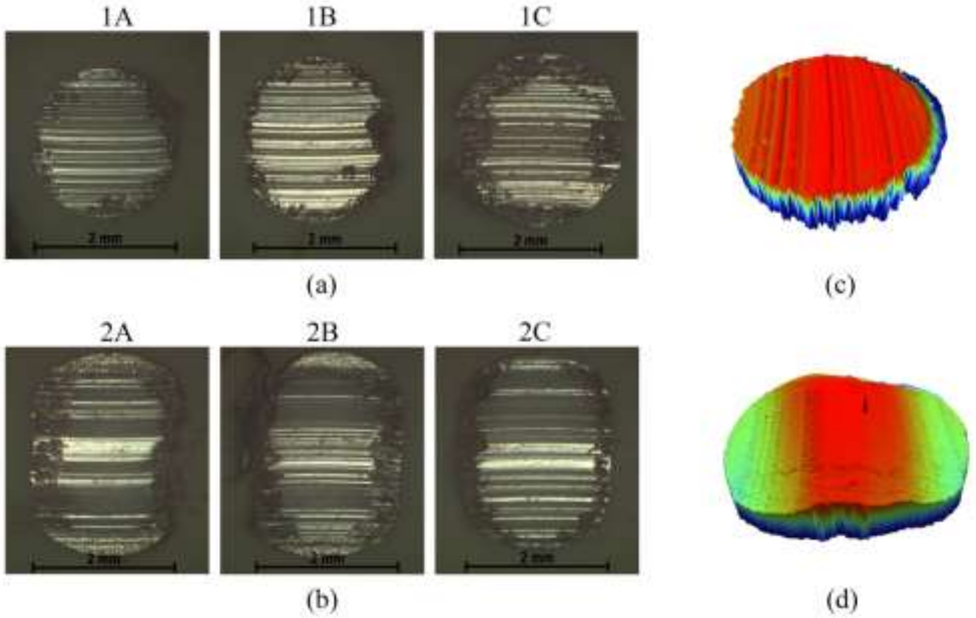


Figure 9. Wear microscopies of balls tested against discs: (a) quenched and (b) normalized; interferometry of a ball tested against a disc: (c) quenched and (d) normalized.

4. CONCLUSIONS

In this work, it was possible to conclude that changes in the hardness level of SAE 1045 steel through heat treatment results in changes of wear severity.

Regarding the microstructure, quenched discs did not obtain a uniform martensitic structure along the disc thickness due to the low 1045 steel hardenability and the disc thickness itself, which resulted in an insufficient cooling rate. However, on a layer close to the surface (about 30 μm), martensite was formed, which gave the quenched discs a surface hardness of 286 HB, 50% higher than those measured on the normalized discs.

The coefficient of friction measured in the tests with the quenched discs was higher than the normalized ones. This difference can be associated with the presence of perlite on normalized discs surfaces, which presents lamellar cementite that favors the sliding of the crystalline planes and the reduction of friction.

The expected mechanisms (abrasion and adhesion) were observed at the end of the tests, which agrees with the literature. There was also a considerable wear increase on discs with low hardness. This difference is due to the change in the main wear mechanism, being predominantly abrasive in the quenched discs and adhesive in the normalized ones. It was found that this transition can be measured indirectly through the wear shape of the zirconia balls. Balls tested against quenched discs, harder, resulted in circular and flat marks. The balls tested against normalized discs, however, resulted in elliptical marks.

5. ACKNOWLEDGEMENTS

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