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Frictional Ignition of Natural Gas-Air Mixtures by Alternative Coal-Cutter Bit Shank Materials

By L. Garner McDonald

UNITED STATES DEPARTMENT OF THE INTERIOR

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BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	mm	millimeter
in	inch	ms	millisecond
in/min	inch per minute	psi	pound per square inch
ksi	10^3 pound per square inch	rpm	revolution per minute
lb	pound	sfpm	surface foot per minute
μg	microgram	vol pct	volume percent
mg	milligram	wt pct	weight percent
mil	10^{-3} inch		

FRICTIONAL IGNITION OF NATURAL GAS-AIR MIXTURES BY ALTERNATIVE COAL-CUTTER BIT SHANK MATERIALS

By L. Garner McDonald[1]

ABSTRACT

The U.S. Bureau of Mines tangentially impacted potential coal-cutter bit shank materials against sandstone to investigate the potential of the materials to ignite natural gas by a friction-generated hot streak. The shank material samples were mounted in a 24-in, 550-lb flywheel, which was rotated at surface speeds of 400 to 900 sfpm. The sandstone was advanced toward the rotating flywheel at feed rates of 1 mil per impact. The atmosphere mixture was 7 vol pct natural gas in air. Three grades of polycarbonate resin, an ultra-high-molecular weight polyethylene, and a zinc alloy (ZA27) were among the potential materials. None of these materials caused ignition of the methane at any of the three test speeds (400, 600, and 900 sfpm), but the above materials do not have sufficient strength to hold a carbide tip during coal cutting. Of the materials having sufficient strength to hold a carbide tip, three nickel-based alloys proved less likely to cause a natural gas ignition than did iron-based alloys such as 4340 (a commonly used shank material for coal cutters).

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INTRODUCTION

Many methane gas explosions in underground coal mines are caused by frictional heating where coal-cutter bits impact sandstone (*1-3*).[2] The ignition factors of air-methane mixtures by heated surfaces have been studied for over two centuries. The investigations have shown that:

- As the surface temperature increased, the size of the heated area needed to incend methane decreased (*4*).
- The most incendive mixture was approximately 6.5 vol pct methane in air (*5-6*).
- The minimum temperature of the hot surface to cause ignition was 640° C (*5-6*).
- A "lag time" existed between getting the surface to a specific incendive temperature and the actual ignition of air-methane mixtures (*7*).

The ignition of firedamp, methane, and natural gas resulting from the impact between metallic and rock materials has been investigated by many researchers. Some of the results from the Safety in Mines Research Establishment (SMRE) of England have shown that:

- An oblique, sliding impact between two materials easily ignited air-methane mixtures (*8*).
- The time to ignition was an inverse function of both the load squared and the speed of cutting to the fourth power. (The load was applied to the sliding metal sample perpendicular to the contact surface between the sandstone and the metal.) (*9*)
- The temperature at the impact surfaces approaches the melting point of the metal while the bulk of the metal remains cool (*10*).
- There was no direct relationship found between the lathe cutting forces and the ease of ignition as the metallic sample cut a helical path into rotating sandstone (*11*).

The U.S. Bureau of Mines also has been active in methane incendivity research. Various Bureau researchers have studied the effect of temperature and surface area (*12*), the effect of different types of sandstone and other rock materials (*13-15*), and the effect of near-tangential impacts by coal-cutter steels and other cutting tool materials against rock (*13-14, 16-17*). They concluded that:

- Methane incendivity increased with cutting speed.
- The cause of ignition was the frictionally generated hot streak on the sandstone immediately behind the impact.
- The maximum temperature of the hot streak was achieved within 2 ms and ranged from 1,200° to 1,400° C, but rapidly decreased to less than 800° C within 40 msec after the impact.
- The steel shank is two to five times more likely than the cemented carbide tips to cause gas ignition.

The work reported in this report compared the performance of 4340, a coal-cutter shank material, against possible substitutes for 4340 in the tool shank. Both nonferrous metal alloys and polymeric materials were investigated.

ACKNOWLEDGMENT

Strength requirement calculations for cutting of No. 6 coal are courtesy of George Laird, mechanical engineer, Albany Research Center.

EXPERIMENTAL EQUIPMENT AND MATERIALS

EQUIPMENT

The frictional ignition chamber (FIC), shown in figure 1, was composed of 1/4-in steel walls with angle iron braces. The FIC dimensions were 44 by 36 by 18 in. There were two 1-in thick polycarbonate[3] viewing ports and one 16-in mylar plastic (1 mil thick) rupture-vent port. The top-viewing port was a 14-in submarine type hatch that allowed ready access for changing the shank materials and sandstone blocks.

The shank material samples were 3/8 in square by 1-1/2 to 3 in long. They were mounted in a 24-in, 550-lb flywheel within the chamber (fig. 2). The flywheel was driven by a hydraulic motor using a variable speed, variable displacement hydraulic pump. The pump was driven by a 15-hp electric motor. The rotational speed of the flywheel ranged from 55 to 160 rpm (350 to 1,000 sfpm).

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[2] Italic numbers in parentheses refer to items in the list of references preceding the appendixes at the end of this report.

[3] Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

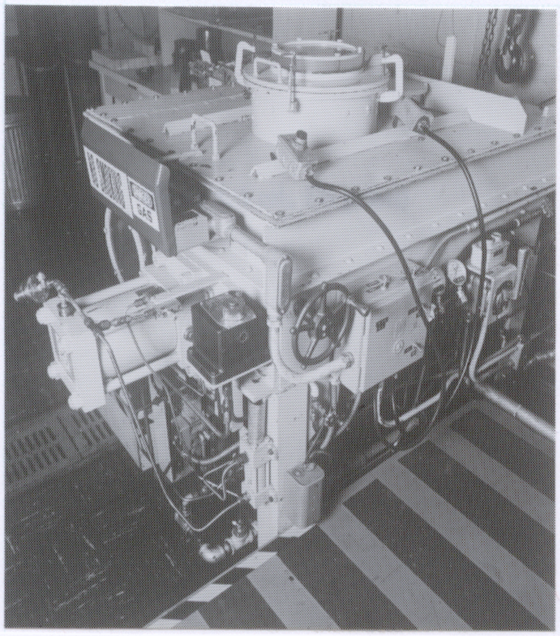

Figure 1.—Frictional ignition chamber. Note: 6-in hydraulic cylinder located outside explosion chamber (left-center).

The sandstone block was secured to a steel-holding table that could be moved radially, tangentially, or axially to the flywheel. The table was advanced radially by a 6-in bore hydraulic cylinder. A micrometering valve on the cylinder head inlet port controlled the sandstone block feed rate from 0 to 2 ipm (actual test feeds were set to advance the sandstone toward the flywheel at 1 mil/rev). The location of the 6-in cylinder projecting from the left end of the FIC is shown in figure 1.

The sandstone holding table also had the capability to be advanced tangential to the flywheel using the 3-1/4-in hydraulic cylinder shown in figure 2. Axial motion to the flywheel was accomplished by a manually operated screw drive. The screw drive and 3-1/4-in cylinder were used to position the sandstone so that four to six kerfs could be made on each side of the sandstone block.

Pressure transducers were located at the side ports on the head of the two hydraulic cylinders (6-in bore radial feed and 3-1/4-in bore tangential motion). Pressure measurements from the transducers were fed through signal conditioners to a digitizing oscilloscope and microcomputer analyzing system where they were converted to radial and tangential forces and stored on 5-1/4-in floppy disks. Figure 3 shows the oscilloscope-microcomputer analyzing system.

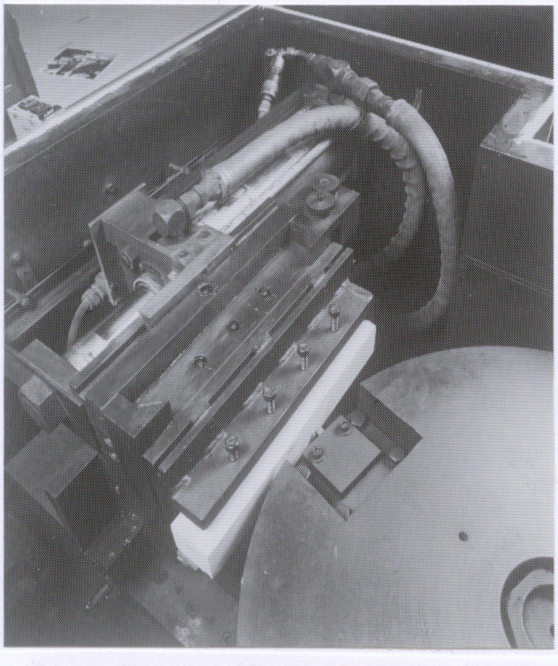

Figure 2.—Sandstone holding fixture and flywheel. Sandstone block and shank material are in test position (lower center). Note: 3-1/4-in hydraulic cylinder is located inside chamber (upper center).

Figure 3.—Frictional ignition chamber with oscilloscope and microcomputer analyzing system for determining radial and tangential impact forces.

MATERIALS

The composition of the gas-air mixture used in the experiment was 7 vol pct natural gas (natural gas composition is given in table 1).

Table 1.—Composition analysis of natural gas, volume percent

CH_4	92.7-92.9	N_2	1.7-2.0	O_2	0.15-0.2	CO_2	<0.1
C_2H_6	2.4- 2.6	C_3H_8	.7-1.0	CO	<.1	H_2	<.1

The sandstone used in the investigation was a fine-grain quartzitic sandstone called Ohio Blue from McDermitt, OH. The sandstone is a dark gray, clayey, feldspathic, very fine-grain sandstone with some parallel bedding. It has a clastic texture consisting of rounded grains of quartz, some feldspar, and trace amounts of muscovite, pyrite, amphiboles, pyroxenes, and diatoms. The cement is mostly argillaceous material.

The materials investigated in this program were three steels, a zinc based alloy, three nickel-cobalt alloys, a nitrided niobium-titanium-tungsten alloy, and four polymeric materials (table 2). The compositions of the metallic alloys investigated here and, for comparison, four alloys investigated by Blickensderfer, Deardorff, and Kelley (*13*) are shown in table 3.

Table 2.—Properties and descriptions of test shank materials

Material	Tool No.[1]	UTS, ksi	YS, ksi	Elongation, pct	Hardness
METALLIC ALLOYS					
ZA27 sandcast Zn alloy[2]	1	58-64	53-54	3-6	HB 110-120
Ni-Co cast alloys:					
87Ni-13Co	62	ND	ND	ND	ND
90Ni-10Co	63	ND	ND	ND	ND
10Ni-90Co	64	ND	ND	ND	ND
NICON nitrided refractory metal alloy[3]	68	ND	ND	ND	ND
Steels:					
1018 plain carbon steel	69	58-60	32-54	15-25	HB 116-126
A2 tool steel, quenched and tempered	70	265	230	4	HRC 58
4340 low-alloy steel, quenched and tempered[4]	5,71	235	210	15	HRC 48
POLYMERIC MATERIALS					
Polycarbonate resins:					
Lexan 141, medium viscosity[5]	2	9.5	9	110	HRM 70
Lexan 500, high rigidity, toughness, and impact strength[5]	3	9.6	8	10-20	HRM 85
Lexan 3412, glass fiber (20 vol pct) reinforced[5]	4	16	ND	4-6	HRM 91
Special A-R ultra-high-molecular weight polyethylene, abrasion resistant[6]	6	5.6	ND	470	HRM 67

HB	Brinell hardness.
HRC	Rockwell C hardness.
HRM	Rockwell M hardness.
ND	Not determined.
UTS	Ultimate tensile strength.
YS	Yield strength.

[1] Material test sample number.
[2] Provided by Noranda Corp. through the auspices of the Zinc Institute, Inc.
[3] Provided by Fansteel Corp.
[4] A commonly used coal cutter shank steel.
[5] Provided by General Electric Co.
[6] Provided by Industrial Plastics, Inc.

Table 3.—Compositions of nonpolymeric materials

Material	*Composition, pct*
CURRENT RESEARCH	
ZA27 sandcast Zn alloy	70+ Zn, 27 Al, 2.25 Cu
Ni-Co cast alloys:	
87Ni-13Co	87 Ni, 13 Co
90Ni-10Co	90 Ni, 10 Co
10Ni-90Co	90 Co, 10 Ni
NICON nitrided refractory metal alloy	50 Cb, 30 Ti, 20 W
Steels:	
1018 plain carbon steel	99+ Fe, 0.75 Mn, 0.18 C
A2 tool steel	90+ Fe, 5.25 Cr, 1.1 Mo, 1 C, 0.6 Mn, 0.25 V, 0.2 Si
4340 low-alloy steel	96+ Fe, 1.8 Ni, 0.8 Cr, 0.7 Mn, 0.4 C, 0.3 Si, 0.25 Mo
PRIOR RESEARCH[1]	
Rene 41 Ni alloy	52+ Ni, 19 Cr, 11 Co, 10 Mo, 3 Fe, 3 Ti, 1.5 Al, 0.1 C
Armco Fe	99.9+ Fe
Steels:	
4130 alloy steel	97+ Fe, 1.0 Cr, 0.5 Mn, 0.3 C, 0.3 S, 0.2 Mo
17-4 pH stainless steel	74+ Fe, 16.5 Cr, 4.3 Ni, 3.5 Cu, 0.5 Si, 0.4 Mn, 0.04 C

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[1] Alloys used by Blickensderfer, Deardoff, and Kelley (*13*) are included for comparison with alloys used in current program.

EXPERIMENTAL PROCEDURES AND CONDITIONS

PROCEDURES

A sample of the shank material was loaded into the flywheel of the ignition chamber. The chamber was infused with natural gas to a 7 vol pct concentration. The sample was impacted against the sandstone at speeds of 400, 600, or 900 sfpm and a feed rate of 1 mil per impact. The test was terminated at ignition or 300 impacts, whichever came first. A step-by-step sequence for the operation of the frictional ignition chamber is given in appendix A.

TEST CONDITIONS

The independent test variables were shank material and peripheral speed of the flywheel. The flywheel was rotated at 400, 600, and 900 sfpm.

The controlled conditions were the sandstone (Ohio Blue), the gas-air mixture (7 vol pct natural gas in air), the feed rate toward the flywheel (1 mil per impact), and the clearance angle between the sandstone and test material (minus 3°).

Preliminary tests established the clearance angle that was most likely to cause ignition to be between minus 1° and minus 4°. An angle of minus 3° (fig. 4), was selected for all subsequent testing. Such a configuration corresponds to a badly worn or damaged tool in an actual continuous mining machine. Previous researchers have shown that sharp cutting tools rarely, if ever, cause frictional ignition. Only after a wear land developed on the tool did ignition occur (*14, 15, 18*).

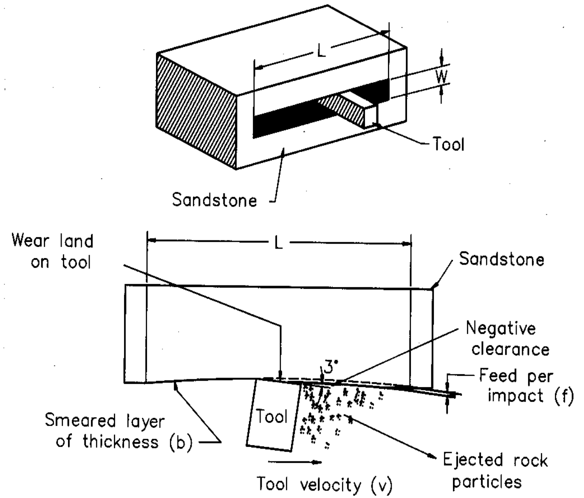

Figure 4.—Configuration of sandstone and tool: top, perspective; bottom, horizontal section.

RESULTS AND DISCUSSION

The effect of cutting speed for each material tested on ignition and number of impacts to ignition are summarized in table 4. The raw data for all of the materials and variables are tabulated in appendix B. Figures 5 through 11 show the effects of speed, temperature, and cutting forces on likelihood of ignition.

ALLOYS

The materials evaluated for possible replacement of steels in coal-cutter shanks were three grades of polycarbonate; one grade of wear-resistant, ultra-high-molecular weight polyethylene; three cast Ni-Co alloys; a nitrided Nb-Ti-W alloy and a cast zinc alloy. For comparison purposes, three grades of steel—1018 plain carbon steel, 4340 alloy steel (currently used shank material), and A2 air-hardened tool steel were also tested. The ignition results are shown in order of likelihood of causing an ignition and are summarized as follows:

1. The nitrided Nb-Ti-W alloy (NICON) caused natural gas ignitions on every test run at all three speeds (400, 600, and 900 sfpm).
2. The 1018 steel and 10Ni-90Co cast alloy caused ignitions at all three speeds, but only at 900 sfpm did they cause ignitions on every trial.
3. The A2 tool steel and the 4340 alloy steel caused no ignitions at 400 sfpm, but resulted in ignitions on every trial that was run at 600 and 900 sfpm.
4. The 87Ni-13Co and 90Ni-10Co cast alloys caused no ignitions at 400 sfpm, and did not result in ignitions on every trial at either 600 or 900 sfpm.
5. The four polymers and the cast zinc alloy caused no ignitions on any trial at any of the three speeds.

Alloy steels such as 4340 and 4130 are the most common shank materials currently used. These two steels, with proper heat treatment, have yield strengths above 200,000 psi (*19*). The five materials that caused no ignitions have yield strengths less than 25 pct of this value. ZA27 has a yield strength of 54,000 psi (*20*). The ultimate tensile strengths for LEXAN 141, 500, and 3412 are 9,500, 9,600, and 16,000, respectively (*21*). The Special A-R polyethylene has an ultimate tensile of 5,600 psi (*22*). Simple calculations using resultant force measurements from Roepke and Voltz (*23*) for the cutting of Illinois No. 6 coal gave strength requirements of 20,000 psi. This value does not include any dynamic affects, such as impact, or softening by frictional heat, which can increase the strength requirements by an order of magnitude. It is not uncommon for the carbide tip to be torn from the steel shank of commercial cutters and the shank near the tip to be badly deformed. This suggests that conditions occur that, on occasion, can exceed the 200,000 psi yield strength of the common shank materials. The strength of the four polymers and the zinc alloy are too low to hold carbide tips during the cutting of coal.

Table 4.—Number of impacts and ignitions for shank materials evaluated in this research (in order of likelihood of ignition)

	NICON alloy	10-Ni-90Co	1018 carbon steel	4340 alloy steel	A2 tool steel	87Ni-13Co	90Ni-10Co	ZA27 Zn alloy	Polycarbonate resins			Special A-R polyethylene
									Lexan 141	Lexan 500	Lexan 3412	
Cutting speed, sfpm:												
400	200*	320	308	315	310	348	355	308	310	304	304	ND
	190*	311	307	301	309	308	351	305	302	ND	ND	ND
	170*	304	306	300	304	308	322	ND	ND	ND	ND	ND
	159*	253*	304	ND	302	304	306	ND	ND	ND	ND	ND
	ND	ND	301	ND	300	ND	302	ND	ND	ND	ND	ND
	ND	ND	144*	ND	ND	ND	ND	ND	ND	ND	ND	ND
600	114*	307	313	162*	150*	315	314	310	320	313	315	304
	108*	190*	159*	147*	137*	314	310	ND	304	ND	ND	ND
	93*	153*	131*	65*	112*	314	306	ND	ND	ND	ND	ND
	86*	150*	118*	55*	96*	180*	129*	ND	ND	ND	ND	ND
900	60*	132*	92*	56*	118*	306	320	325	365	318	320	333
	57*	130*	86*	53*	89*	237*	273*	307	346	315	314	307
	56*	96*	68*	47*	74*	230*	243*	307	332	310	309	304
	51*	66*	37*	33*	69*	216*	111*	306	321	307	306	ND
	ND	63*	ND	ND	ND	183*	80*	303	312	ND	ND	ND
	ND	ND	ND	ND	ND	130*	77*	301	307	ND	ND	ND
Ignitions per trial:	1	0.69	0.57	0.73	0.62	0.43	0.40	0.0	0.0	0.0	0.0	0.0

ND Not determined.

NOTE.—Asterisk indicates ignition of gas mixture occurred.

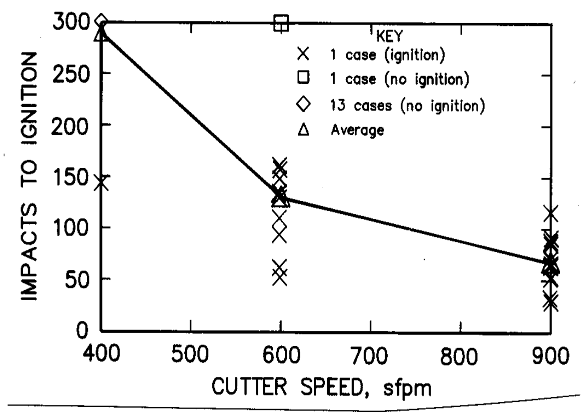

Figure 5.—Effect of speed on number of impacts to ignition of 7 vol pct natural gas-air mixture for steels impacting sandstone. Averages are calculated assuming ignition occurred at 300 impacts for each "no ignition" case.

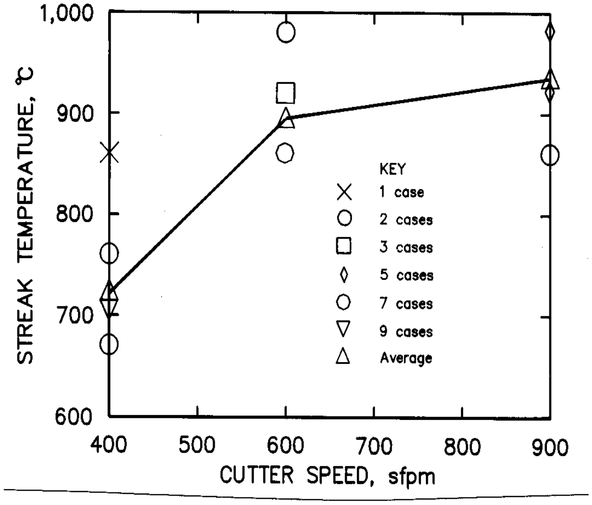

Figure 6.—Effect of speed on streak temperature of 7 vol pct natural gas-air mixture for steels impacting sandstone.

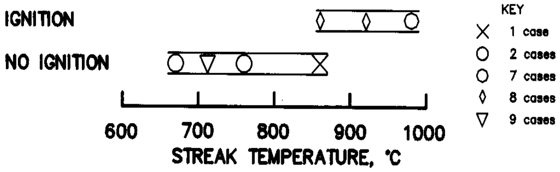

Figure 7.—Effect of streak temperature on ignition of 7 vol pct natural gas-air mixture for steels impacting sandstone.

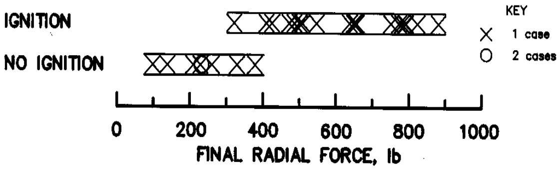

Figure 8.—Effect of final radial force on ignition of 7 vol pct natural gas-air mixture for steels impacting sandstone.

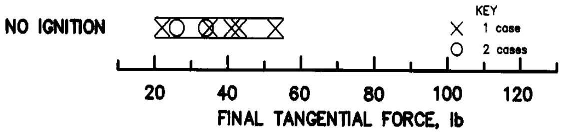

Figure 9.—Effect of final tangential force on ignition of 7 vol pct natural gas-air mixture for steels impacting sandstone.

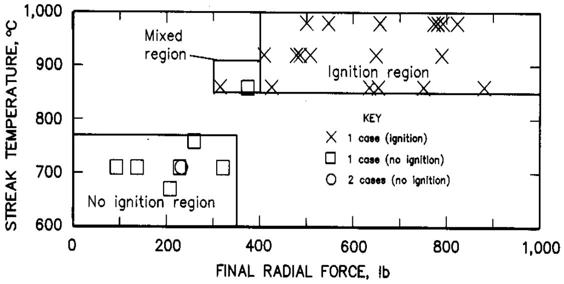

Figure 10.—Effect of final radial force on streak temperature in 7 vol pct natural gas-air mixture for steels impacting sandstone.

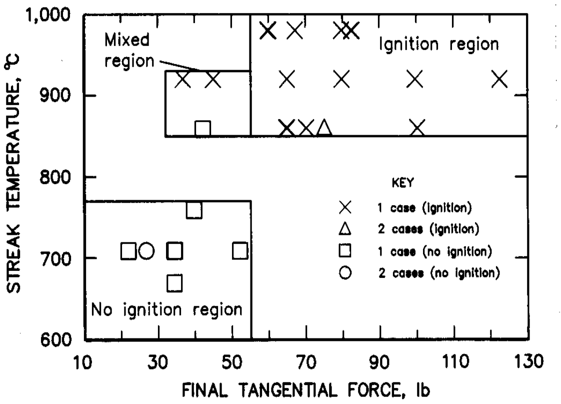

Figure 11.—Effect of final tangential force on streak temperature in 7 vol pct natural gas-air mixture for steels impacting sandstone.

Of the remaining materials in table 4, the NICON, while surely strong enough, too readily causes ignitions at all cutting speeds to be used as a coal-cutter material. The 1018 carbon steel with a maximum yield strength of only 54,000 is not strong enough to hold the carbide during coal cutting. The 10Ni-90Co cast alloy causes some ignitions at the lowest cutting speed and is composed primarily of the strategic and expensive metal cobalt. The A2 tool steel is more expensive than 4130 or 4340 without providing any extension of tool life or improved safety from reduced likelihood of ignition. The 87Ni-13Co and 90Ni-10Co alloys are shown to be less likely to cause an ignition than any of the steels in table 4. This improved safety of nickel-based alloys is confirmed in table 5 obtained from the data of Blickensderfer, Deardorff, and Kelley (*13*). The nickel-based alloy Rene 41 was shown to be less likely to cause an ignition than the three iron-based alloys—Armco Iron, 4130 steel, and precipitation hardening stainless steel with composition of 17 Cr and 4 Ni (*13*).

CUTTING SPEED

Many researchers have reported that as cutting speed increases, the ease of ignition increases (*5, 11, 14, 24*). In this research, as the speed of the steels increased, the likelihood of ignition increased from 7 pct at 400 sfpm, to 92 pct at 600 sfpm, and 100 pct at 900 sfpm. Furthermore, the number of impacts required to get an ignition dropped as speed was increased. Figure 5 shows this drop in impacts as a function of speed. To get natural gas ignition at 900 sfpm generally required about 69 impacts; while at 600 sfpm the requirement was 137 impacts; and by 400 sfpm the ignition of natural gas required 292 impacts.

There is not a lot of information in the literature about the relationship between speed and temperature, but it has been proposed that the increase in ignition probability with speed is because of an increase in area of the hot streak exposed to the gas, not because of higher temperature (*14*). The current research found that as speed increased, temperature increased (fig. 6). Thus the increasing likelihood of ignition with increasing speed is caused not only by the increased hot streak area, but also by an increase in temperature of the hot streak.

Table 5.—Number of impacts and ignitions for shank materials cited in reference 13

	Feed, mils per impact	4130 alloy steel	17-4 pH stainless steel	Armco Fe	Rene 41
Cutting speed, sfpm:					
300	0.8	308	326	250	300
	3	190	130	137	137
450	0.8	178*	342	333	302
	3	161	97	131	59*
	6	61	60	61	115
	12	30	36	31	26*
600	0.8	175*	166*	79*	300
	3	154*	126	126	124
	6	29*	24*	73	42*
	12	39*	16*	32*	29
750	0.8	172*	306	170*	310
	3	165	92	120*	115*
	6	27*	20	75	38*
	12	14*	28	32*	21*
900	0.8	76*	93*	125*	305
	3	55*	86	108*	128
	6	63*	14*	48	40*
	12	11*	9*	24*	22*
1100	0.8	70*	103*	143*	305
	3	132*	74*	97*	136
	6	28*	18*	53	60
	12	8*	4*	15*	10*
Ignitions per trial:		0.73	0.50	0.50	0.41

NOTE.—Asterisk indicates ignition of gas mixture occurred.

TEMPERATURE

A definite relationship was found between ignition occurrence and hot streak temperature (fig. 7). No ignitions occurred below hot streak temperatures of 860° C. Powell (*6*) reported a minimum temperature of 640° C for a nonfriction heated surface to cause methane-air mixture ignition. Blickensderfer (*14*) found maximum temperature for friction caused hot streaks to be 1,200°-1,400° C at 2 ms after impact, but the hot streak rapidly cooled to a maximum of 800° C by 40 msec after impact. Naylor and Wheeler (*7*) showed that there is a "lag time" between getting a surface to a specific temperature and the ignition of methane-air mixtures, also the lower the specific temperature, the longer the "lag time." The most likely explanation of why there were no ignitions between the 860° C of this research and the minimum temperature of

640° C (*6*) is that with the rapidly decreasing temperature of the hot streak after impact (*14*), there is insufficient lag time (*7*) to allow the ignition of the gas mixture.

IMPACTING FORCES

Except for a single data point overlap (figs. 8 and 10), no ignition occurred where final radial forces were at or below 380 lb and all ignitions occurred when the final radial forces were at or above 320 lb. A similar pattern holds for the final tangential forces. Figures 9 and 11 show, in general, ignitions occurred for final tangential forces greater than 53 lb. Figures 10 and 11 show that a relationship exists between streak temperature, final forces, and likelihood of ignition. While Rae (*9*) reported an inverse relationship between time and the square of the sliding load, this research found no one-for-one relationship between number of impacts to ignition and impacting forces.

CONCLUSIONS

1. The three polycarbonate resins (LEXANS 141, 500, and 3412) and the ultra-high-molecular weight polyethylene (Special A-R) caused no ignitions at any of the three speeds, but do not have sufficient strength to hold the carbide tip during coal cutting.
2. The Zn-Al alloy (ZA 27) caused no ignitions at any of the three speeds, but, while significantly stronger than the four plastics, was deemed not to have sufficient strength to hold the carbide tip during coal cutting.
3. The nitrided Nb-Ti-W alloy (NICON) caused ignitions on every trial at all three speeds and was, therefore, considered dangerous to use as a coal-cutter material in underground mines.
4. The 1018 steel and the 10Ni-90Co cast alloy caused some ignitions at the lowest speed (400 sfpm) and was, therefore, not recommended for coal-cutter materials in underground mines.
5. The A2 tool steel had a similar performance record as the 4340. There were no ignitions at the lowest speed, but there were ignitions on every trial at the two higher speeds. Since A2 tool steel is more expensive than 4340, there are no reasons to justify substitution of A2 for 4340.
6. The two Ni-base cast alloys were shown to be less likely to cause an ignition than 4340.
7. Some interrelationships between test parameters were also found for the steels:
   a. All ignitions occurred where the hot streak temperature was 860° C or higher.
   b. As speed increased, the likelihood of ignition increased.
   c. As speed increased, the temperature of the hot streak at ignition rose.
   d. In general, ignitions occurred at or above 320 lb final radial force and 53 lb final tangential force.

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APPENDIX A.—FRICTIONAL IGNITION CHAMBER OPERATING PROCEDURES

Normal operating sequence for the frictional ignition chamber:

1. Sandstone was loaded into the holding fixture. All sandstone was held in a drying oven at 140° C until ready for loading.
2. Shank material sample was weighed and loaded into the flywheel.
3. Ignition chamber was sealed by closing the top port and installing the 1 mil mylar rupture diaphragm.
4. Natural gas was charged into the chamber until the gas-air mixture was 7 vol pct natural gas. Natural gas volume was measured by a wet test (flow) meter. As the gas entered at the top of the chamber, a small vent was opened at the bottom to allow air to escape, thereby maintaining ambient air pressure in the chamber. The vent was closed when gas infusion was completed.
5. Gas and air were mixed thoroughly in the chamber with a spark-resistant safety fan for a minimum mixing time of 5 min.
6. The flywheel hydraulics were engaged and the wheel set to the desired speed by adjusting the pump flow.
7. The flywheel was disengaged and all accumulators charged.
8. The sandstone radial feed rate was set to provide 1 mil per impact.
9. The oscilloscope-microcomputer was engaged for acquisition of cutting force data.
10. The flywheel was engaged again, and the sandstone was moved radially toward the flywheel.
11. If ignition did occur within 300 impacts, the test was terminated and pressurized air vented into the chamber to expel all combustion products before the top port was opened.
12. If ignition did not occur within 300 impacts, the flywheel was stopped and a spark plug was energized to ignite the air-gas mixture. Pressurized air was vented into the chamber to expel all combustion products. For safety reasons, the number of impacts was limited to just over 300. The test samples extended 0.375 in from the flywheel and, at 1 mil per impact, 300 impacts left a safe operating distance between the sandstone and the flywheel.
13. The test sample was removed; sample and sandstone were examined for amount and type of smears; test sample was then cleaned and weighed, and the kerf chord length on the sandstone was measured.
14. Throughout the run, two observers noted the color of the hot streak on the sandstone just behind the test sample. If ignition occurred, then the color of that impact was logged. If no ignition occurred, then the color was recorded at impact number 300.

APPENDIX B.—FRICTIONAL IGNITION DATA TABLE

Table B-1.—Frictional ignition data (No data = -9)

Tool No.[1]	Run No.	Run month	Cutting speed, sfpm	Ignition[2]	Hot streak color[3]	Number of impacts	Weight loss, mg	Weight loss per impact	Smear on tool, µg	Smear on sandstone[4]	Forces, lb.				Temp,[5] °C	Kerf cord length, mm	Kerf area, mm^2
											AFR	AFT	FFR	FFT			
62A1	2760	12	400	1	1.5	304	176.6	580.92	3	13	113.06	44.2	99.3	19.0	630	111	1,062.8
62A2	2791	1	900	1	4.5	306	55.3	180.72	3	3	229.16	60.9	352.9	71.4	920	92	879.5
62A3	2825	1	600	1	4.0	314	132.3	421.34	3	12	310.27	38.7	243.3	29.6	860	110	1,053.2
62A4	2868	2	600	1	3.0	315	131.4	417.14	3	22	412.07	40.6	256.8	27.9	760	105	1,004.8
62A5	2908	3	900	10	4.5	237	56.7	239.24	3	3	638.13	49.5	1,054.8	77.2	920	74	706.5
62A6	2933	3	400	1	2.0	348	190.5	547.41	3	1	229.21	36.3	55.2	14.2	670	122	1,169.5
62B1	2766	1	400	1	2.0	308	116.8	379.22	3	13	91.47	69.4	79.5	39.0	670	178	1,719.0
62B2	2985	4	900	10	4.0	183	40.3	220.22	3	3	484.46	67.3	706.9	61.6	860	71	677.7
62B3	2833	1	400	1	2.5	308	156.2	507.14	3	3	151.71	33.9	73.4	20.0	710	122	1,169.5
62B4	2855	2	900	10	4.5	130	21.0	161.54	3	23	570.50	62.0	938.8	74.7	920	54	515.0
62B5	2893	2	600	1	5.0	314	141.5	450.64	3	2	484.10	68.1	477.7	47.2	980	110	1,053.2
62B6	2926	3	600	10	4.0	180	75.6	420.00	3	3	499.51	51.4	463.9	66.8	860	76	725.7
62B7	2973	4	900	10	4.5	216	44.8	207.41	3	2	-9.00	-9.0	-9.0	-9.0	920	86	821.7
62B8	2788	1	900	10	5.0	230	60.5	263.04	3	3	-9.00	-9.0	-9.0	-9.0	980	82	783.3
63A1	2754	12	400	1	3.0	351	127.0	361.82	3	12	147.70	54.1	170.4	34.8	760	113	1,082.2
63A2	2986	4	900	10	4.5	77	9.2	119.48	3	3	403.49	42.7	668.2	67.6	920	40	381.3
63A3	2853	1	900	1	4.0	320	51.7	161.56	3	3	750.11	50.2	1,375.1	79.4	860	94	898.7
63A4	2873	2	600	1	4.5	310	117.4	378.71	3	3	478.68	39.8	425.2	42.1	920	103	985.5
63A5	2925	3	600	10	4.5	129	36.8	285.27	3	3	474.60	69.5	582.6	92.0	920	65	620.2
63A6	2957	4	900	10	4.5	80	48.7	608.75	3	3	-9.00	-9.0	-9.0	-9.0	920	35	333.5
63B1	2775	1	400	1	2.5	302	155.8	515.89	2	13	148.99	49.4	119.0	25.1	710	122	1,169.5
63B2	2811	1	600	1	5.0	306	115.2	376.47	3	3	367.80	76.0	393.4	51.9	980	105	1,004.8
63B3	2790	1	900	10	4.5	243	53.1	218.52	3	3	-9.00	-9.0	-9.0	-9.0	920	77	735.3
63B4	2840	1	900	10	4.5	273	34.2	125.27	3	1	941.87	66.5	1,375.1	83.4	920	53	505.4
63B5	2934	3	400	1	1.5	322	127.7	396.58	3	11	190.75	32.8	60.8	18.2	630	121	1,159.8
63C1	2777	1	900	10	6.0	111	17.8	160.36	3	3	135.52	42.1	189.0	60.3	1,130	49	467.2
63C2	2966	4	400	1	2.5	306	157.6	515.03	3	12	105.92	55.2	80.1	22.7	710	120	1,150.1
63C3	2879	2	600	1	4.0	314	105.2	335.03	3	3	612.76	47.4	604.7	37.3	860	103	985.5
63C4	2818	1	400	1	2.5	355	159.2	448.45	3	13	-9.00	-9.0	-9.0	-9.0	710	122	1,169.5
64A1	2758	12	400	1	2.0	320	112.5	351.56	3	11	126.42	59.9	136.1	59.5	670	117	1,121.0
64A2	2795	1	900	10	4.5	63	7.2	114.29	3	3	113.85	21.8	195.0	39.0	920	42	400.3
64A3	2827	1	600	10	4.5	153	39.2	256.21	3	23	449.82	38.8	556.6	50.4	920	70	668.1
64A4	2864	2	600	10	4.5	150	32.1	214.00	3	3	531.48	41.9	659.9	47.4	920	71	677.7
64A5	2913	3	900	10	4.5	130	14.6	112.31	3	23	528.17	39.9	900.1	48.6	920	58	553.2
64A6	2935	3	400	1	2.5	311	128.8	414.15	3	11	292.23	42.2	116.0	21.5	710	123	1,179.2
64B1	2763	12	400	1	3.0	304	65.4	215.13	3	13	78.95	31.4	82.8	25.3	760	105	1,004.8
64B2	2982	4	900	10	4.5	66	14.2	215.15	3	3	358.12	43.3	610.2	73.3	920	40	381.3
64B3	2830	1	400	10	3.0	253	108.3	428.06	3	13	206.94	46.0	149.3	25.8	760	117	1,121.0
64B4	2856	2	900	10	4.5	132	16.4	124.24	3	23	535.60	42.9	969.2	45.6	920	58	553.2
64B5	2885	2	600	10	4.5	190	58.7	308.95	3	23	551.70	66.6	610.2	62.4	920	81	773.7
64B6	2919	3	600	1	4.5	307	82.4	268.40	3	2	472.51	49.2	662.7	54.7	920	112	1,072.5
64B7	2787	1	900	10	5.5	96	24.0	250.00	3	23	-9.00	-9.0	-9.0	-9.0	1,060	49	467.2

See notes following table.

Table B-1.—Frictional ignition data (No data = -9)—Continued

Tool No.[1]	Run No.	Run month	Cutting speed, sfpm	Ignition[2]	Hot streak color[3]	Number of impacts	Weight loss, mg	Weight loss per impact	Smear on tool, µg	Smear on sandstone[4]	Forces, lb.				Temp,[5] °C	Kerf cord length, mm	Kerf area, mm[2]
											AFR	AFT	FFR	FFT			
68A1	3060	2	900	10	5.0	60	0.4	6.67	0	1	48.20	6.8	294.1	32.8	980	47	448.1
68A2	3069	2	600	10	5.5	93	0.3	3.23	0	1	67.19	14.9	226.2	50.6	1,060	61	581.9
68A3	3077	2	400	10	4.0	200	0.5	2.50	2	12	70.15	23.1	386.5	80.9	860	97	927.6
68B1	3061	2	900	10	5.5	56	0.3	5.36	2	1	34.71	6.2	275.7	40.6	1,060	45	429.0
68B2	3070	2	600	10	5.5	108	0.4	3.70	0	1	62.78	14.9	201.9	48.1	1,060	58	553.2
68B3	3078	2	400	10	4.0	190	0.2	1.05	2	12	72.70	14.3	226.2	38.2	860	95	908.4
68C1 ...	3062	2	900	10	5.5	57	0.3	5.26	2	1	46.80	9.0	352.0	43.1	1,060	49	467.2
68C2 ...	3071	2	600	10	5.5	114	0.4	3.51	0	1	89.65	17.5	295.2	48.1	1,060	68	649.0
68C3 ...	3079	2	400	10	4.5	170	0.3	1.76	1	1	51.60	16.4	179.5	60.6	920	87	831.3
68D1 ...	3063	2	900	10	5.5	51	0.1	1.96	1	1	33.77	5.7	295.2	43.1	1,060	42	400.3
68D2 ...	3072	2	600	10	5.5	86	0.2	2.33	0	1	105.83	17.2	259.0	55.6	1,060	57	543.7
68D3 ...	3080	2	400	10	4.5	159	0.3	1.89	2	1	61.96	20.0	134.6	48.1	920	90	860.2
69A1	2835	1	400	1	3.0	306	173.0	565.36	3	13	287.98	42.4	259.6	40.7	760	118	1,130.7
69A10 ..	2952	3	400	10	4.0	144	87.3	606.25	3	23	459.14	65.1	425.2	75.3	860	132	1,266.7
69A11 ..	2954	3	400	1	2.5	308	190.0	616.88	3	22	405.09	70.3	231.9	34.8	710	83	792.9
69A12 ..	2988	4	400	1	2.0	307	190.3	619.87	23	3	-9.00	-9.0	-9.0	-9.0	670	79	754.5
69A13 ..	2990	4	400	1	2.5	301	180.7	600.33	3	12	218.10	44.3	93.9	22.3	710	124	1,188.9
69A14 ..	2950	3	600	10	4.0	118	36.7	311.02	3	3	556.30	61.1	751.1	71.3	860	68	649.0
69A2	2859	2	900	10	4.5	37	1.1	29.73	3	2	237.06	22.3	408.6	34.0	920	28	266.8
69A3	2881	2	600	1	4.0	313	34.7	110.86	3	3	504.80	48.7	378.3	42.7	860	105	1,004.8
69A4	2911	2	900	10	4.5	92	8.5	92.39	3	2	301.40	29.3	472.2	43.1	920	46	438.5
69A5	2929	3	600	10	5.0	159	48.2	303.14	3	3	551.08	75.6	657.2	83.4	980	72	687.3
69A6	2937	3	400	1	2.5	304	187.6	617.11	3	11	-9.00	-9.0	-9.0	-9.0	710	117	1,121.0
69A7	2944	3	900	10	5.0	86	9.0	104.65	3	23	436.26	48.2	773.1	71.7	980	41	390.8
69A8	2946	3	900	10	5.0	68	6.3	92.65	3	23	317.40	38.9	499.8	58.7	980	42	400.3
69A9	2948	3	600	10	4.0	131	43.5	332.06	3	3	477.15	76.1	635.1	100.5	860	71	677.7
70A1	2836	1	400	1	2.5	302	178.8	592.05	3	3	285.71	61.4	231.9	53.1	710	124	1,188.9
70A10 ..	2951	3	600	10	4.5	112	37.6	335.71	3	23	550.88	90.6	789.7	98.4	920	128	1,227.8
70A11 ..	2953	3	400	1	2.5	310	211.1	680.97	3	3	506.35	45.6	328.6	26.3	710	64	610.7
70A12 ..	2955	3	400	1	2.5	309	206.8	669.26	3	22	465.51	43.9	229.2	25.9	710	123	1,179.2
70A13 ..	2991	4	400	1	2.5	300	188.6	628.67	3	12	305.30	56.6	138.1	34.4	710	124	1,188.9
70A2	2860	2	900	10	5.0	89	9.0	101.12	3	2	487.19	46.0	792.4	59.7	980	47	448.1
70A3	2882	2	600	10	5.0	137	35.8	261.31	3	3	595.62	56.8	822.8	79.0	980	72	687.3
70A4	2912	3	900	10	4.0	118	16.5	139.83	3	3	449.53	44.7	880.8	74.5	860	52	495.9
70A5	2930	3	600	10	4.5	150	37.9	252.67	3	3	489.63	46.1	648.9	64.8	920	70	668.1
70A6	2938	3	400	1	2.5	304	178.7	587.83	3	12	-9.00	-9.0	-9.0	-9.0	710	124	1,188.9
70A7	2945	3	900	10	5.0	74	7.5	101.35	3	23	393.05	51.1	546.7	68.5	980	44	419.4
70A8	2947	3	900	10	5.0	69	8.5	123.19	3	23	465.48	45.8	781.4	66.4	989	45	429.0
70A9	2949	3	600	10	4.0	96	23.6	245.83	3	3	525.91	54.8	654.4	-9.0	860	63	601.1
71A	2362	2	400	1	2.5	300	147.2	490.67	3	23	-9.00	-9.0	-9.0	-9.0	710	123	1,179.2
71A	2374	3	400	1	3.0	301	116.7	387.71	3	13	-9.00	-9.0	-9.0	-9.0	760	125	1,198.6
71A	2363	2	600	10	4.0	65	41.4	636.92	3	13	-9.00	-9.0	-9.0	-9.0	860	78	744.9
71A	2375	3	600	10	4.0	162	76.3	470.99	3	13	-9.00	-9.0	-9.0	-9.0	860	105	1,004.8
71A	2364	2	900	10	4.5	33	27.8	842.42	3	23	-9.00	-9.0	-9.0	-9.0	920	62	591.5
71A	2376	3	900	10	4.5	56	42.0	750.00	3	3	-9.00	-9.0	-9.0	-9.0	920	62	591.5

See notes following table.

Table B-1.—Frictional ignition data (No data = -9)—Continued

Tool No.[1]	Run No.	Run month	Cutting speed, sfpm	Ignition[2]	Hot streak color[3]	Number of impacts	Weight loss, mg	Weight loss per impact	Smear on tool, µg	Smear on sandstone[4]	Forces, lb.				Temp,[5] °C	Kerf cord length, mm	Kerf area, mm^2
											AFR	AFT	FFR	FFT			
1A1	4002	7	400	1	0.0	308	2,689.9	8,733.44	0	23	-9.00	-9.0	-9.0	-9.0	-9	68	649.0
1A2	4039	9	600	1	0.0	310	1,240.4	4,001.29	0	23	-9.00	-9.0	-9.0	-9.0	-9	69	658.6
1B1	4003	7	900	1	0.0	307	1,034.1	3,368.40	20	23	-9.00	-9.0	-9.0	-9.0	-9	62	591.5
1B2	4032	9	900	1	0.0	303	581.4	1,918.81	0	3	-9.00	-9.0	-9.0	-9.0	-9	47	448.1
1C1	4008	7	900	1	0.0	307	1,326.6	4,321.17	0	23	-9.00	-9.0	-9.0	-9.0	-9	75	716.1
1C2	4037	9	900	1	0.0	306	1,199.3	3,919.28	0	23	-9.00	-9.0	-9.0	-9.0	-9	59	562.8
1D1	4010	7	900	1	0.0	325	884.4	2,721.23	0	23	1,588.90	49.7	2,008.7	60.0	-9	63	601.1
1E1	4019	7	900	1	0.0	301	576.1	1,913.95	0	23	1,655.10	62.2	2,595.5	88.9	-9	53	505.4
1E2	4028	7	400	1	0.0	305	2,282.6	7,483.93	0	2	86.40	27.5	92.5	26.3	-9	62	591.5
2A1	4005	7	900	1	0.0	318	507.4	1,595.60	0	3	253.60	9.7	41.9	9.3	-9	0	0.0
2B1	4007	7	900	1	0.0	315	537.6	1,706.67	0	3	247.10	10.7	91.1	7.9	-9	0	0.0
2C1	4013	7	900	1	0.0	310	665.7	2,147.42	0	3	-9.00	-9.0	-9.0	-9.0	-9	0	0.0
2D1	4014	7	900	1	0.0	307	683.5	2,226.38	0	0	222.40	11.5	37.3	8.5	-9	0	0.0
2E1	4021	7	600	1	0.0	313	398.8	1,274.12	0	3	360.40	11.6	314.8	8.3	-9	0	0.0
2F1	4025	7	400	1	0.0	304	571.7	1,880.59	0	3	301.10	13.0	226.4	8.1	-9	0	0.0
3A1	4004	7	900	1	0.0	320	463.3	1,447.81	0	3	168.60	13.0	39.4	9.7	-9	0	0.0
3B1	4009	7	900	1	0.0	314	680.2	2,166.24	0	0	180.30	10.8	80.1	10.9	-9	0	0.0
3C1	4015	7	900	1	0.0	306	653.0	2,133.99	0	3	221.90	11.4	105.0	12.2	-9	0	0.0
3D1	4016	7	900	1	0.0	309	422.7	1,367.96	0	1	160.10	10.6	58.7	8.9	-9	0	0.0
3E1	4022	7	600	1	0.0	315	456.0	1,447.62	0	0	364.90	12.7	285.8	14.2	-9	0	0.0
3F1	4026	7	400	1	0.0	304	639.1	2,102.30	0	3	468.30	10.4	494.2	13.0	-9	0	0.0
4A1	4001	7	400	1	0.0	302	702.9	2,327.48	0	0	-9.00	-9.0	-9.0	-9.0	-9	0	0.0
4A2	4040	9	600	1	0.0	304	439.3	1,445.07	0	3	-9.00	-9.0	-9.0	-9.0	-9	0	0.0
4B1	4006	7	900	1	0.0	346	675.6	1,952.60	0	3	-9.00	-9.0	-9.0	-9.0	-9	0	0.0
4B2	4030	9	900	1	0.0	321	304.5	948.60	0	3	-9.00	-9.0	-9.0	-9.0	-9	0	0.0
4C1	4011	7	900	1	0.0	365	745.1	2,041.37	0	0	111.30	15.2	46.3	8.9	-9	0	0.0
4D1	4012	7	900	1	0.0	307	659.8	2,149.19	0	3	-9.00	-9.0	-9.0	-9.0	-9	0	0.0
4D2	4034	9	900	1	0.0	332	570.4	1,718.07	0	3	-9.00	-9.0	-9.0	-9.0	-9	0	0.0
4E1	4018	7	900	1	0.0	312	557.8	1,787.82	0	3	187.80	11.0	58.7	8.9	-9	0	0.0
4F1	4023	7	600	1	0.0	320	420.5	1,314.06	0	3	212.00	16.8	51.1	8.3	-9	0	0.0
4G1	4027	7	400	1	0.0	310	554.3	1,788.06	0	3	515.20	14.0	517.8	13.4	-9	0	0.0
5A1	4017	7	900	10	4.5	47	8.9	189.36	3	2	263.40	47.5	486.0	79.4	920	43	409.9
5C1	4020	7	600	10	4.5	55	12.4	225.45	3	2	379.20	59.9	508.1	123.1	920	46	438.5
5D1	4024	7	600	10	4.0	147	53.5	363.95	3	12	285.00	50.8	314.8	64.4	860	77	735.3
5D2	4029	7	400	1	2.0	315	164.3	521.59	3	11	224.50	57.2	208.5	34.0	670	124	1,188.9
5D3	4035	9	900	10	4.0	53	9.7	183.02	3	12	-9.00	-9.0	-9.0	-9.0	860	53	505.4
6A1	4031	9	900	1	0.0	307	64.8	211.07	0	1	-9.00	-9.0	-9.0	-9.0	-9	0	0.0
6B1	4033	9	900	1	0.0	333	188.7	566.67	0	1	-9.00	-9.0	-9.0	-9.0	-9	0	0.0
6C1	4036	9	900	1	0.0	304	173.9	572.04	0	1	-9.00	-9.0	-9.0	-9.0	-9	0	0.0
6D1	4038	9	600	1	0.0	304	98.5	324.01	0	3	-9.00	-9.0	-9.0	-9.0	-9	0	0.0

AFR Average radial force. AFT Average tangential force. FFR Final radial force. FFT Final tangential force (LB).

[1] See table 2 in text for tool numbers and material descriptions.

[2] 10 = yes and 1 = no.

[3] Hot streak colors: 0 = dark; 1 = first glow in dark room ~590° C; 2 = dull red ~670° C; 3 = bright red ~760° C; 4 = red-orange ~860° C; 5 = orange ~980° C; 6 = orange-yellow ~1,130° C; 7 = yellow ~1,320° C; 8 = yellow-white ~1,550° C; and 9 white ~1,830° C.

[4] Smear: 0 = no smear; 1 = light; 2 = medium; 3 = heavy; x = gray to black powder; 1X = glassy; and 2X = metallic.

[5] Hot streak temperature estimated from streak color.

[6] Calculated from f(CL) × 9.525 (test sample width).