Research Article

Effect of Gear Composition and Soil Interaction on Surface Wear of Worm Gear of Self Propelled Rotary Hoe

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Abstract | This study was conducted on a self-propelled locally made rotary hoe to overcome a problem of frequent transmission failure. The machine is used for mechanical weed control and hoeing. It was observed that the worm gear used in its transmission often failed due to surface wear of gear teeth. Worm gears made from three different copper alloys were tested against soil resistance in sandy loam soil bin. The gears were formed of commercial gun metal (Cu 87.76%, Sn 7.74, Zn 1.52%), gun metal (Cu 88%, Sn 7.38%, Zn 1.78%), and gear bronze (Cu 85.92%, Sn 4.96%, Zn 2.93%, Ni 1.23%). The gear compositions were determined using atomic absorption. The gears under test exhibited significant difference in surface wear among each other. As compared to gear bronze commercial gun metal and gun metal showed surface wear of 245% and 109% respectively. The highest surface wear was observed in commercial gun metal whereas lowest surface wear was observed in gear bronze. It was concluded that gear bronze may be the best material composition for use in the worm gear of the rotary hoe transmission box as compared to the other two alloys tested.

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Introduction

Weeds cause significant loss to crop yield and there are about 25-30% losses in wheat crop on the average due to weeds (Nayyar, 1994). Total monitory losses are very high in Pakistan at national level. Wheat alone exceeds Rs.28 billion loss at national level and Rs.2 billion in Khyber Pakhtunkhwa (Hanif, 2004). Ground water contamination and customer pressure to minimize herbicide use is also pushing the field vegetable and salad producers away from reliance on herbicides. However, contamination of agricultural products with weed leaves or weed seeds need high levels of weed control and this has resulted in the increasing use of hand weeding in organic and conventional crops (Tillett, 2008).

Hand hoeing and finger weeding is popular in Peshawar (Pakistan) valley. It is an effective weed control method. If other methods are not useful and weeds get out of control in the crops, hand hoeing is preferably adapted, which is labor intensive, time consuming, tedious and costly operation. Labour shortage has already been indicated in a report published in 1984 by Pakistan Census of Agricultural Machinery which concluded that the hired labor is on the decline from

7 to 4% in Pakistan. Hand weeding can be greatly reduced through inter-row cultivation (Bowman 1997). In non-chemical weed management in no-till organic farming – mechanical weeding can be effectively implemented as one of possible techniques (Kepner, 1982; Kurstjens, 2007).

The machine transmission is made of worm gear-set. It provides a very large gear ratio in a single mesh as suggested by Shigley et al. (2004) as an outstanding feature of the worm gear-set. Worm gear failure occurred due to surface wear of gear teeth which resulted in reducing gear tooth thickness. According to Shigley et al. (2004) the transmission efficiency gets poor due to a great amount of sliding as the worm tooth engages with its mating worm gear tooth and forces rotation by pushing and sliding that causes friction in worm gear, thus, removing material from the tooth surface of the gear causing surface wear, and reducing weight of the gear. Goldman (1969) and Rooij and Schipper (1998) also assumed in their study that the cause of the worm gear failure could be due to surface wear of gear tooth. Surface wear reduces thickness of the gear teeth which caused bending in teeth. It cannot withstand loads from soil resistance. Transmission box of the machine is driven by a worm and worm gear-set. Worm gear is made of copper alloy known as commercial gun metal while worm is made of carbon steel. In the local market commercial gun metal is a material made from liquefying scrap imported gun metal gears. It was observed from used gears that the gear material used did not exhibit its original composition because of the reprocess. The direct problem found was in the material composition of the worm gear.

Resistance from the soil is affecting machine component (worm gear) of the rotary hoe. The cone penetrometer was used to measure soil strength in the field conditions. According to Dexter et al. (2007), the penetration resistance provides easy and rapid method for determining soil strength. Hernanz et al. (2000) determined penetration resistance of the cylindrical soil probes which were extracted from well drained loamy soil. These probes were compacted at different moisture content using different compaction energies. The penetration resistance values proved to be independent of the cone used, as long as the cone size was equal to or greater than 98 mm^2. The author further indicated that bulk density is an indicator of soil compaction or loosening as it is directly proportional to total soil porosity.

Laser Scanning Confocal Microscopes (LSCM) technique was used by Anamalay et al. (1995) to determine wear surfaces. They reported that the technique has the capability of recording surfaces depth of field upto unlimited range. The authors developed parameters for measuring and analyzing the surfaces using the above LSCM technique. They also compared surface analysis LCSM techniques with the conventional profilometer methods. The authors concluded that LSCM technique used is a valid method for surface analysis as compared to conventional profilometer technique.

Shigley et al. (2004) stated that machine members often fail due to repeated or cyclic loading. The actual stresses produced by such loading are below ultimate strength of the material and also below yield strength. Cause of the failure is repeated stresses for a very large number of times. Such failure of the machine component is known as fatigue failure.

Akinci et al. (2005) conducted an experiment on a rotary tiller and reasoned that the gear failures may be faults of usage, heat treatment, design, manufacture and material. The researchers further reported that failure was due to design error and material fault. The commonly known facts about failure are fracture, surface fatigue, abrasion and plastic deformation in gear transmission. Fracture results from surface fatigue, high load or abrasions. Surface fatigue results from tensile stress, compression stress and sliding stress under the gear surface.

Pak Swiss Agricultural Light Engineering Programme (ALEP) Mardan, through its client customer workshop developed a self-propelled hand held machine for mechanical weed control known as rotary hoe. The machine was locally being manufactured during 1991 and 1995 for five years but was out of production due to its poor performance. According to the manufacturer (Mumtaz Engineering Works, Takht Bhai, Mardan, Khyber Pakhtunkhwa, Pakistan) the machine could hardly perform for a single season. The major problem found was the transmission box breakdown, which transmits power to the rotary cutter shaft. Ten percent of the produced machines were reported with damaged worm gears in the transmission box. However, no information on rest of the machines supplied could be ascertained. It was, therefore, decided to work on the machine to improve its performance. Little research is available on the rotary hoe under study. There could be many causes to the failure such as manufacturing fault, design fault, but material problem seemed to be more evident as the worm gear was usually made from scrap material so called commercial gun metal, which did not perform well. Other failed worm gears observed were not made from correct material either. In many cases it was found by the researcher that only copper was casted. Worm gear failure occurred due to low quality material. Whatever material locally available was used for the gear did not satisfy the load requirement of the rotary hoe transmission.

Rotary hoe under study as well, has worm gear failure problem in the transmission. Accordingly the research has been conducted to investigate the problem of the machine by analyzing the effect of soil resistance and gear composition on surface wear on the gear in controlled condition in a soil bin. The main aim of the study was to determine the strengths and weaknesses of the existing worm gear design and its subsequent performance under field conditions by improving the design of the gears used. The specific objective of this study was to find the surface wear of worm gear teeth of three gear compositions under different soil resistance in the soil bin.

Material and Methods

Description of rotary hoe, method used to evaluate the gear compositions, soil bin preparation, and experimental design to determine surface wear are presented as follows.

Rotary hoe

Agricultural Light Engineering Programme (ALEP) Mardan, through its client customer workshop developed a self-propelled hand held machine for the purpose known as rotary hoe as shown Figure 1. It can inter hoe row crops such as vegetables, maize, tobacco, and sugarcane. The machine is powered by 5 hp engine. Its rotary cutter L-shaped blades in the front of the machine can be adjusted to the row width.

Rotary hoe under study had worm gear failure problem in the transmission box which was due to frequent failure of the gear teeth. During experiments three different gear compositions were compared for surface wear in the gear.

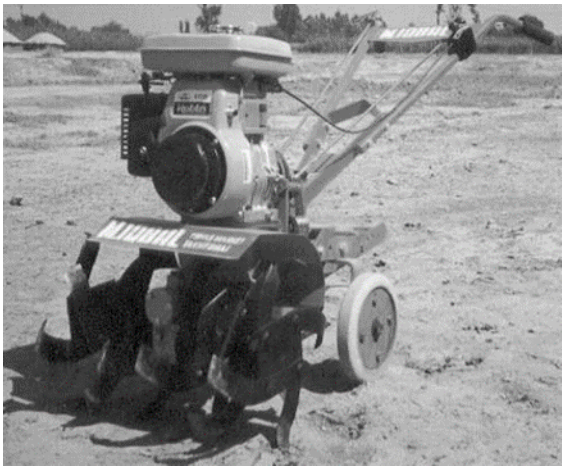

Figure 1: *Rotary hoe manufactured in Takht Bhai, Mardan*

Gear composition

Three different copper alloy worm gears were tested (i.e. commercial gun metal, gun metal and gear bronze) in the machine (Table 1).

The gear compositions were evaluated with wet elemental analysis using atomic absorption. Elemental microanalysis was also done with Dispersive X-ray spectroscopy (EDX). Copper alloy is a common material used for manufacturing worm gear because of its low coefficient of friction with steel worm. Worm and worm gear set exhibits pure sliding therefore more friction is involved in this gear. Table 1 shows material composition of the gears at the time of casting. Commercial gun metal made up from scrap old imported gears was reheated and reprocessed for making required shapes and sizes. The composition of the material does not stay as original gun metal after processing. It varies from casting to casting and from material to material. Solid solutions of other two copper alloys were also casted according to specification shown in the Table 1.

Table 1: *Starting material composition of worm gear used in the experiment*

S.No.	Gear name	Composition
1	Commercial gun metal	88% Cu, 10% Sn, 2% Zn scrap material
2	Gun metal	88% Cu, 10% Sn, 2% Zn
3	Gear bronze	88% Cu, 5.5%Sn, 4%Zn,2.5%Ni

Soil bin

A soil bin, located in The University of Agriculture Peshawar, (Pakistan) Farm was made to test the rotary hoe. The size of the soil bin was 15m x 45m. It was excavated up to 76 cm depth. The bin was then filled with top soil of the farm in the spring 2009. After filling it was irrigated to settle the loose soil. The bin remained undisturbed until completely dried. It was then tilled with cultivator to mix and level the soil. The bin was again irrigated to bring it to about normal farm condition. Moisture content of the soil was tested using oven dry method. Soil texture analysis showed that soil texture of the soil bin was sandy clay loam. Different moisture contents were established by irrigating the bin at different intervals.

The soil bin provides a medium for testing the worm gear of the rotary hoe. Rotary cutters force to cut the soil. Soil reaction on the cutters is transmitted to the worm gear. The opposing torque from the worm develops cyclic stresses in the worm gear teeth, resulting in wear of the worm gear. Soil reaction is the penetration resistance of the soil measured by handheld cone penetrometer (Eijkelkamp, The Netherlands).

Various possible soil resistances were established by providing different soil moisture conditions. The machine was operated in the soil bin from very dry to wet soil, which produced different load conditions.

Experimental Design

To run the experiment, the soil bin was divided lengthwise into 9 equal (1.6m x 45m) plots. Each plot then was randomly selected for testing the machine. Completely randomized design was used. Five soil moisture conditions ranging from 3% to 15% and to field capacity level of 20% were developed. All the three gear composition worm gears were replicated 3 times for all five soil moisture conditions.

Experimentation

Before testing the machine the gearbox was filled with new gear oil (GL-4 SAE 140) each time a new worm gear was assembled for the test and hand held penetrometer reading (N) was taken in each plot at minimum of three different locations randomly. According to Lapen et al. (2004) assessing soil shear strength cone penetration resistance is generally accepted. Penetration resistance varies with change in moisture content generally. The cone had been forced into the soil with uniform hand pressure at the rate of 30.48 mm s^{-1} as per ASAE (1992) Standard Test S313.1. Cone index was calculated by dividing the penetrating force by the base area of the cone (Equation 1) which is considered as shearing resistance of the soil. Penetration resistance was recorded before the rotary hoe was set in the soil bin at minimum of three randomly selected points in each plot at 15-20 cm depth. Three soil samples were randomly collected at the same depth with core samples from each plot in the soil bin for determining bulk density and soil moisture content.

Following equations were used to calculate penetration resistance and bulk density of soil:

$$CI = F/A \quad \ldots\ldots\ldots\ldots (1)$$

Where;
CI = cone index (kPa)
F = normal force (N or lb)
A= base area of the cone (cm^2)

$$\rho_b = (W_d / V_t) = (4\,W_d)/(3.14\,d^2 L) \quad \ldots\ldots\ldots\ldots (2)$$

Where;

ρ_b = Bulk density (gcm^{-3})
W_d = weight of oven dry soil (g)
V_t = Total volume of the soil and voids (cm^{-3})
d = diameter of the core sample (cm)
L = length of the core sampler (cm)

The "universal wear test" is not feasible like other engineering properties. The equipment may be designed to simulate the actual service loading. The wear was defined as "unintentional deterioration resulting from use or environment. It may be considered essentially a surface phenomenon, wear is one of the most destructive influences to which metals are exposed and importance of wear resistance needs no amplification (Anver, 1997). The gears were weighed before and after the test to determine the difference which was considered surface wear of the worm gear tested, which represented the material removed from the teeth surface during rotation of the worm gear causing loss in the weight of the gear. The machine was tested under high stress and low cycle for upto 100 cycles and very dry soil condition where high soil resistance was observed. Before weighing, the gears were cleaned with liquid cleaner and then blow dried with pressurized air. Precision digital scale with two digit accuracy was used. According to Zmitrowicz (2006), wear is mostly due 80 – 90% abrasion, and 8% fatigue wear. To detect wear weighing is the simplest method. It gives the total amount of removed mass, but the distribution of wear depth is unknown in contact surface.

Table 2: *Elemental analysis of material composition with atomic absorption*

Gear composition	Cu %(weight/weight)	Tin %(weight/weight)	Zn %(weight/weight)	Ni %(weight/weight)
Commercial gun metal	87.76	7.74	1.52	0
Gun metal	88	7.38	1.78	0
Gear bronze	85.92	4.96	2.93	1.23

Table 3: *Evaluated microanalysis of material composition using energy dispersive x-ray (EDX) method*

Gear composition	Cu %(weight/weight)	Tin %(weight/weight)	Zn %(weight/weight)	Ni %(weight/weight)
Commercial gun metal	85.20	10.80	3.08	0
Gun metal	78.70	16.79	2.8	0
Gear bronze	77.21	14.41	3.05	1.94

Table 4: *Means comparison of surface wear (weight loss (g) in gears at various moisture levels (SM)*

Gear Composition	Soil moisture content on mass basis (%)					MEANS
	15.5	12.5	16.0	16.5	21.0	
Commercial gun metal (manufacturer gear)	0.33	0.30	0.67	0.37	0.23	0.38 A*
Gun metal	0.23	0.20	0.43	0.17	0.13	0.23 B*
Gear bronze	0.13	0.10	0.10	0.13	0.07	0.11 C*

**Means followed by the same letters are not significantly different. LSD (0.05)= 0.1228*

Results and Discussion

Elemental wet analyses of the gear composition were performed with atomic absorption. Table 2 showed Copper, zinc and tin with some percent variation by weight between commercial gun metal and gun metal, whereas gear bronze has addition of nickel. Elemental microanalysis of the copper alloys was also conducted by using Energy Dispersive X-ray Spectrometry (EDX) shown in Table 3. Elemental percent variation was observed among the two analyses because of homogeneity of wet analysis.

Figure 2 shows EDX spectrum for a sample of commercial gun metal which identified copper, zinc and tin. EDX spectrum of sample of gun metal is shown in Figure 3 also identified copper and zinc and tin. Figure 4 represents EDX spectrum of sample of gear bronze showing copper, zinc, tin and nickel. Gear bronze composition has additional element Ni, which may have changed the properties of the solid solution of gear bronze. The variation in the data recorded for atomic absorption and EDX may be due to the fact that in atomic absorption a homogenous mixture of alloy is used while in EDX a specific micro-region is examined.

Surface wear in worm gears

Three different copper alloy worm gears were tested for surface wear under different soil moisture conditions. The result showed significant difference in surface wear of different worm gears of the three compositions. Three gear compositions were compared using soil resistance. The result showed that there is significant difference in the surface wear of different gear compositions. Commercial gun metal showed highest surface wear while the gear bronze gave minimum surface wear. Gear bronze showed the least surface wear among the three gear compositions (Table 4).

The depth of the material removed from the surface in unit time is termed as wear rate (Sharif, 2006). It is in practice that hard/soft material is used for worm gear-set where worm is made of hard steel and worm gear is made of bronze due to its high sliding between the teeth of worm gear. This is done to prevent scuffing. The consequence of this arrangement is that the bronze gear wear rate is very high as compared to conventional gearing. It is being ignored because of many advantages of worm gears.

Results of statistical analysis showed that surface wear of the three different gears among each other is significantly different. Table 4 shows the surface wear

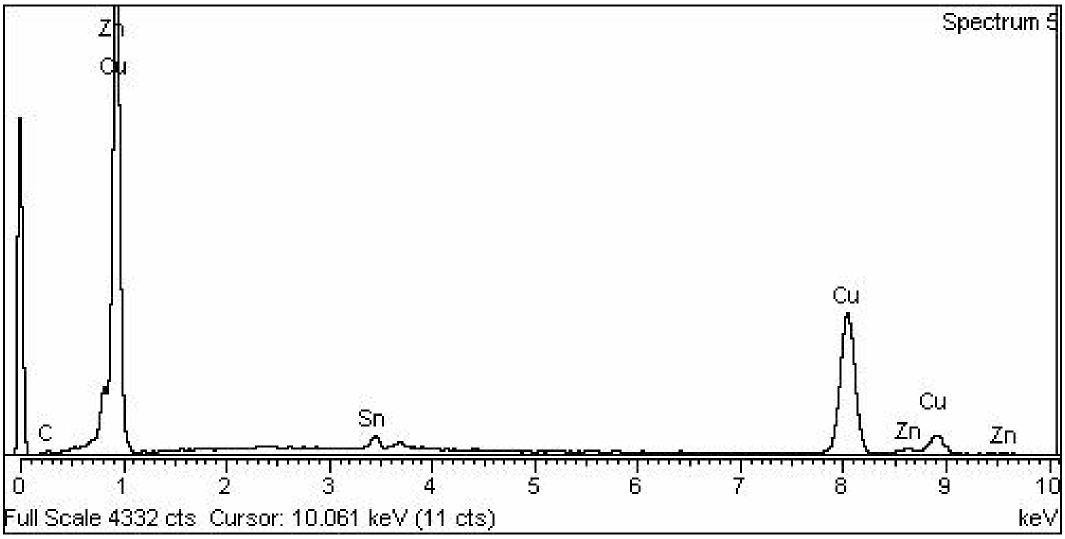

Figure 2: *EDX spectrum of a Commercial gun metal sample, copper, zinc and tin are identifiable*

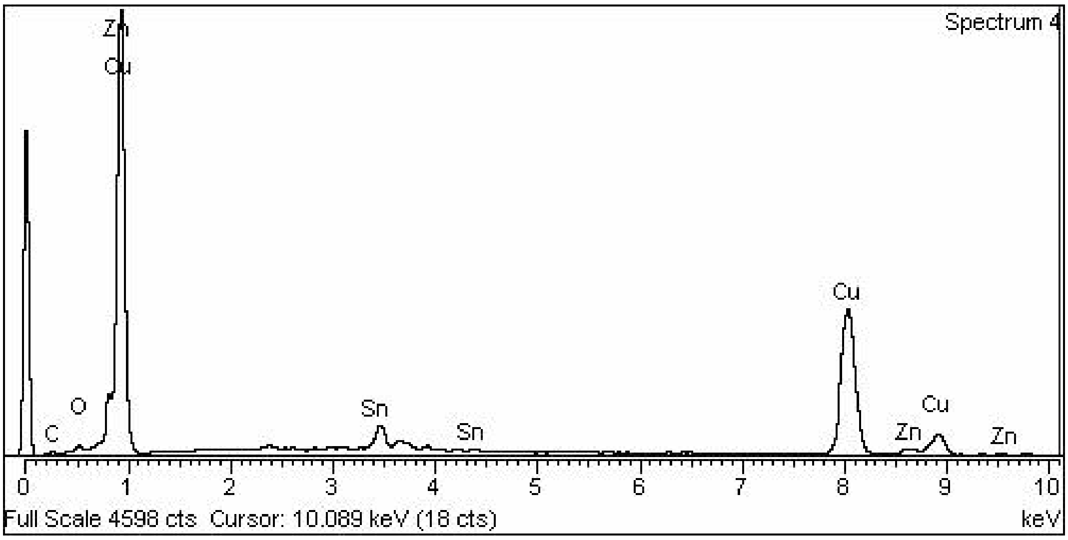

Figure 3: *EDX spectrum of a gun metal. Copper, zinc and tin are identifiable*

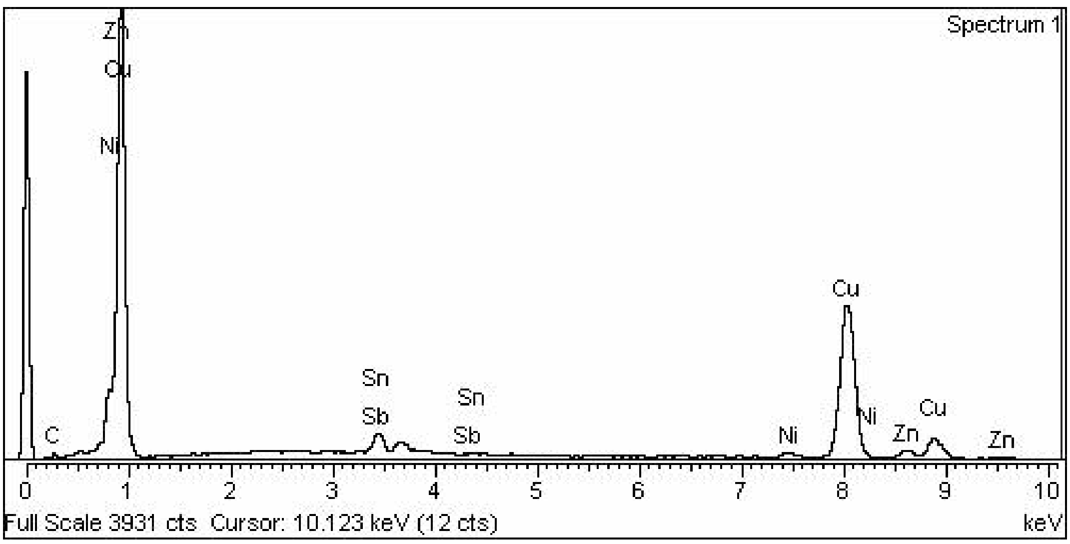

Figure 4: *EDX spectrum of gear bronze sample. Copper zinc, nickel, and tin are identifiable*

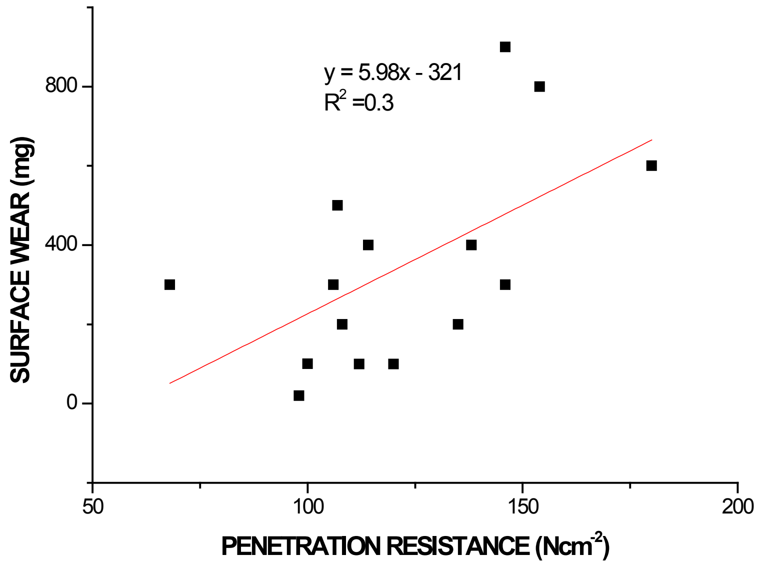

Figure 5: *Effect of Soil Resistance on surface wear of gear composition*

means comparison of the three gear compositions. As compared to gear bronze commercial gun metal and gun metal showed surface wear of 245% and 109% respectively. The lowest surface wear gear bronze may be associated with addition of Ni in the gear. It may be because of precipitation hardening during curing process. Surface wear was measured by determining difference in weight of worm gear before and after the test as it is the simplest way of detecting wear (Zmitrowicz, 2006).

Five moisture levels were used for changing penetration resistance of the soil in the soil bin (i.e. SM1, SM2, SM3, SM4, and SM5). The experiments showed that all the three gear material compositions showed significantly different surface wear.

The relationship between surface wear and soil penetration resistance is shown in Figure 5. It can be seen from the figure that the surface wear was significantly affected by the soil penetration resistance with coefficient of correlation (r) of 0.5412 (Gomez et al., 1984). In general, the surface wear showed an increasing trend with the increase in penetration resistance.

Conclusions and Recommendation

It was concluded that gear bronze is the best choice among the three tested gear compositions. Due to its least surface wear, this gear will last longer during the machine operation. Gear bronze metal composition for manufacturing these low cost gears is very important and our study found that gear bronze metal was the best copper alloy to be used for manufacturing worm gears in comparison to other two alloys tested in this study. The material composition which showed least surface wear may be tested in the machine for further perfecting. The availability of pure and standard material for the best worm gears tested in the study is required to keep the service life of the machine at its maximum. Quantification by weight and purity of the material is needed as well as the casting process should also be done with high skill. Standardization of gear material may be ensured as well as the processes involved for casting the gears.

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