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Understanding Cooling Rate Response of Test Pieces and Actual Gears Using Heat Treat Simulation

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Abstract

The cooling history of carburized heat-treated gears plays a significant role in developing microstructure, hardness, and residual stress in the tooth that influences the fatigue performance of the gear. Evaluating gear carburizing heat treatment should include a microstructure and hardened depth evaluation. This can be done on an actual part or with a test piece. The best practice for a test piece is to use a section size that closely approximates the cooling rate at the gear flank of the actual gear. This study furthers work already presented showing the correct test piece size that should be used for different gear modules (tooth thicknesses). Metallurgical comparisons between test pieces, actual gears, and FEA simulations are shown.

Introduction

Test pieces are often used for hardened depth and microstructure checks of carburized and quench hardened components, so that actual components are not destroyed for the sake of quality assurance. For gear heat treatment, this is especially important because of costly prior processing steps. The "Case Depth" measured in a test piece can be a good indicator of how the gears are carburized and quenched and whether it meets the heat treatment specification requirements. The "Case Depth" normally refers to the depth at which the hardness is equivalent to HRC 50, or some other specified value mentioned in the specification [1]. It also relates to the carbon level and is usually specified as the depth at which carbon falls to 0.40 wt% or 0.35 wt% [2].

The evaluation of microstructures in a test piece can provide insight into formation of retained austenite, grain boundary carbides and surface or case non-martensitic transformation products (NMTP) such as bainite and pearlite. High retained austenite or grain boundary carbide formation lets the heat treater know there is a problem with high carbon potential and the presence of pearlite and bainite at the surface or in the near surface regions lets the heat treater know the quench was inadequate. A surface carbon check provides some assurance that the total carburizing cycle left the surface carbon in an acceptable range. This range is usually about 0.7-1.0 wt. % carbon but can vary by specification. These kinds of quality examinations are best done on an actual part, but significant cost savings can be gained by using a test piece. The test piece must be of the same grade of steel and should preferably be of a similar chemical composition and hardenability. A DI (ideal diameter) variance of more than +/-7 mm can be significant. The test piece must also be of a similar mass or section size in order to properly approximate the quenching quality aspects of the process.

ISO and AGMA provide guidance regarding representative test piece for gears to monitor the interactions of the heat treatment process [3,4]. As per ISO 6336-5 guidance, the minimum diameter should be 3 times of gear module (gear pitch diameter over number of teeth) and the minimum length is 6 times of module. The test piece material shall be equivalent to the part for chemistry and hardenability. AGMA 923-B05 recommends a minimum diameter of test piece of 6 times of module, but not less than 5/8-inch diameter. The minimum length is 2 times its diameter. The test piece, placed with the heat treat load, is intended to represent the metallurgy of the heat-treated tooth section.

Ideally, the test piece will have the same cooling rates at the surface and near surface regions as the actual parts do. In the case of heat-treating gears, the gear tooth flank or active profile is where the surface and case microstructure are most important and one of the places where the case depth (or hardened depth) must be known. If a test piece is allowed in the quality plan, it must do a good job of approximating the quenched mass in this region. Heat treat simulation is a tool that can be used to assure that the cooling rates in the case regions of the test piece is very close to those in the case of the flank of a given size gear tooth.

It is a good practice to always run some correlations between actual gears and whatever test piece is selected. By evaluating test pieces and gears together from the same load or tray, confidence is gained in the evaluation method and in the simulation methods.

This research focuses on a study to determine the proper size and materials of a cylindrical test piece that could be used as an appropriate indicator of the hardened depth and microstructure of the actual gears.

Methodology

A set of numerical experiments are performed using finite element heat treatment simulation of gears of modules varying from 4.78 to 11.3, as shown in Table 1. Solid models of gears are shown in Figure 1. Most of the gears are bevel gear with a shaft attached to them. A parameter defined as characteristic length is introduced and presented in the table to analyze the cooling characteristics of the gear and to compare with the representative test piece size. The parameter borrows from the Chvorinov's Rule parameter used to estimate solidification time in castings [5]. The parameter is estimated as the volume of the gear excluding the shaft divided by the tooth surface area exposed for cooling. Figure 2 depicts the relationship between module and the characteristic length $\left(= V_{gear}/A_{tooth\,surf}\right)$ of gear used in this study. Higher the gear size (pitch diameter) higher the module and the characteristic length.

Table -1 Gear dimensions used for the simulation.

Gear #	Matl	Module	$V_{gear}/A_{tooth\ surf}$
A	AISI 4122	5.08	9.74
B		5.6	13.32
C		6.8096	12.26
D		8.7588	16.77
E		7.9749	18.52
F		13.21054	21.78

Heat treatment simulation is performed using Ansys Mechanical with DANTE UserMat subroutine. DANTE contains the material data such as specific heat, conductivity, mechanical behavior, and phase transformation kinetics of various commercial steel alloys [6-7]. It uses Ansys Mechanical's diffusion/thermal and stress/displacement solvers to predict the part's response to various heat treatment processes.

Eight test pieces of diameters varying from 0.75 to 3 inches are considered for comparison. The test pieces and gears are simulated for carburization process with 1 mm case depth target and followed by direct oil quench. The cycle parameters used for the simulation are presented in Table 2. The material chemistry is shown in Table 3. This is a typical 4120M type carburizing steel and is a one of the standard material selections for DANTE. DANTE utilizes a surface Heat Transfer Coefficient (HTC) vs. temperature characteristic curve for a given quench condition. The selection here was for a "rolling oil", which is an industry fast oil but at low agitation rates. This curve defines the cooling characteristics at the surface of the part, but the part geometry will define the ultimate near surface cooling rates.

Table 2: Cycle parameters used for the simulation.

	Temperature, °C	Time, s	Carbon Potential (wt%)
Carburization	927	14700	1.15
	860	4500	0.9
Quenching from	850		

Gear A

Gear B

Gear C

Gear D

Gear E

Gear F

Figure 1 Solid model of gears being simulated.

The heat treatment simulation will allow a good comparison of cooling rates throughout the cylinder section of the test piece and throughout a gear tooth on the gear. This information can then be used to establish proper test piece diameter sizes for different gear geometries.

A non-linear mesh formulation was used in the finite element model so that smaller elements were near the surface and large elements in the core of the gear and cylinder. Temperature and cooling rate information that extracted for the simulation need to be most accurate in the first 1 mm of depth from the surface (in the case region) for understanding hardened depth comparisons or microstructure comparisons that come from cooling rate differences.

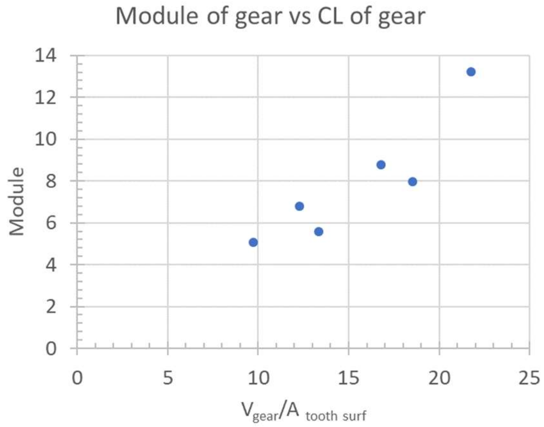

Figure 2 Module of gears vs the characteristic length of gears used for simulation.

Table 3: Chemistry of the steel simulated by DANTE as a part of the standard material library.

	AISI 4122 mod
C	0.21
Mn	0.90
Ni	0.04
Cr	0.87
Mo	0.22
Cu	0.07

Results and Discussion

Temperature history and corresponding cooling rate for cylindrical test pieces of 0.75 to 3-inch diameter are depicted in Figures 3 at a depth of 1 mm. Quenching starts at 10-sec timelines in the time history to consider the part transfer time from the furnace to quench tank. The maximum cooling rate in test pieces varies from 77 °C/s for 0.75-inch to 47 °C/s for 3-inch at a depth of 1 mm from the surface at the mid-height of the test piece, as shown in Figure 3. At a depth of 1.5 mm, it varies from 72 to 43 °C/s, and at a depth of 2 mm it is 69 to 41 °C/s. It should be noted that the time to maximum cooling rate increases with an increase in test piece diameters.

A single tooth section of the gear is modeled to reduce the computational time. A cut section of gear-A with hardness and martensite volume fraction distribution is shown in Figure 4.

Figures 5-10 respectively show the temperature and cooling rate history of gear A-F at the mid-flank location on the tooth at a depth of 1 mm. Plots for the cylinder with different diameters at mid-height location and a depth of 1 mm are also shown in the figures. The maximum cooling rate for gear A with module 5.08 matched well with the 0.75-inch dia. test piece, as shown in Figure 5.

Figure 6 depicts the cooling history of Gear-B with module 5.6. The maximum cooling rate of 1.25-inch dia. test piece matched with that of Gear-B. On the other hand, Gear-C with a module of 6.8 has a close match with a 1.00-inch dia. test piece, as shown in Figure 7. Figures 8-10 show the cooling history of Gears-D and Gear-E and Gear-F, respectively.

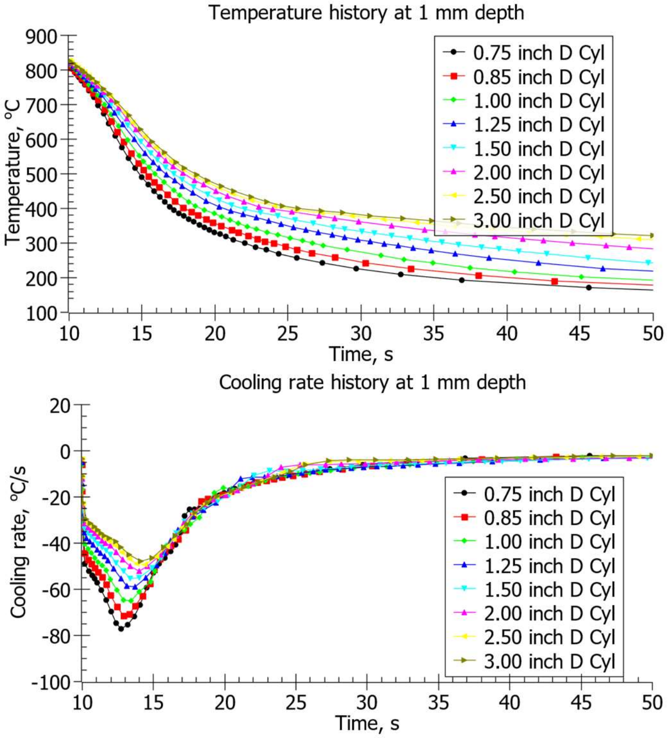

Figure 3 Temperature and cooling rate history of cylindrical test pieces at a depth of 1 mm and at mid-height location.

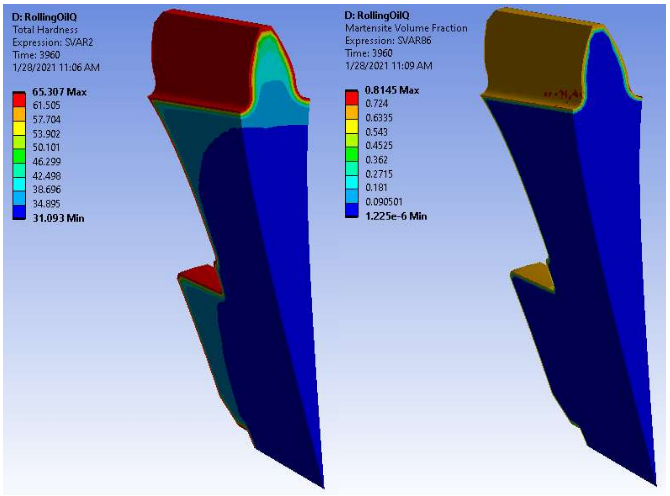

Figure 4 Hardness and martensite distribution after carburization and quenching for gear A

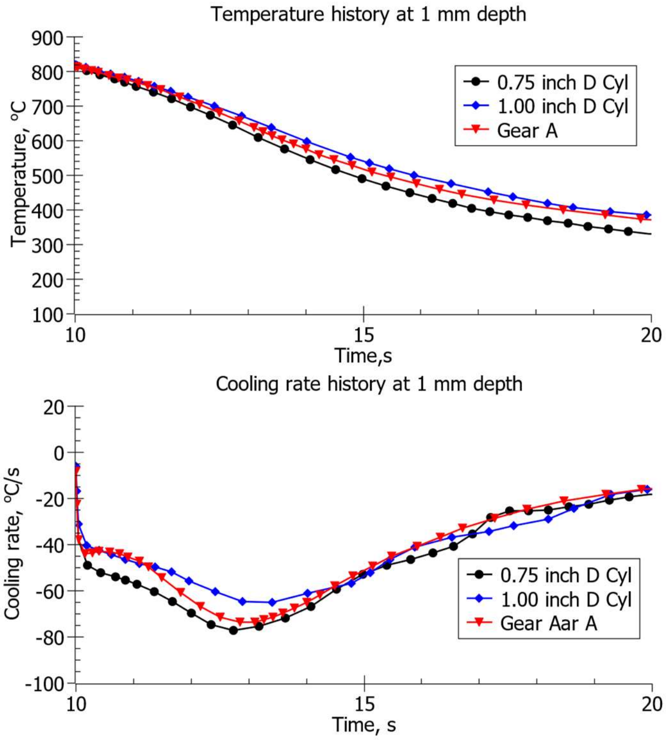

Figure 5: Temperature and Cooling rate history of Gear A at a depth of 1 mm at the mid-flank location and 0.75 inch and 1-inch dia test pieces at the mid-height location

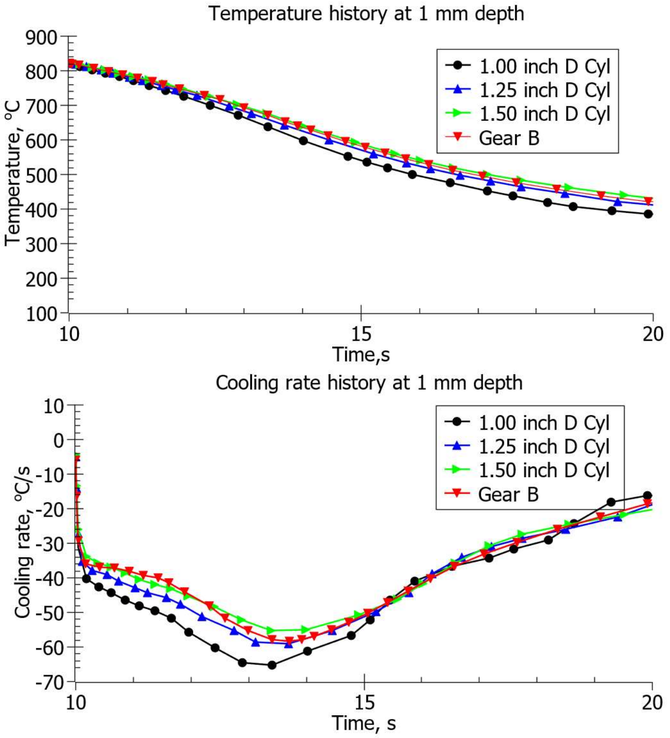

Figure 6: Temperature and Cooling rate history of Gear B at a depth of 1 mm at the mid-flank location and 1.00-inch, 1.25 inch and 1.50-inch dia test pieces at the mid-height location

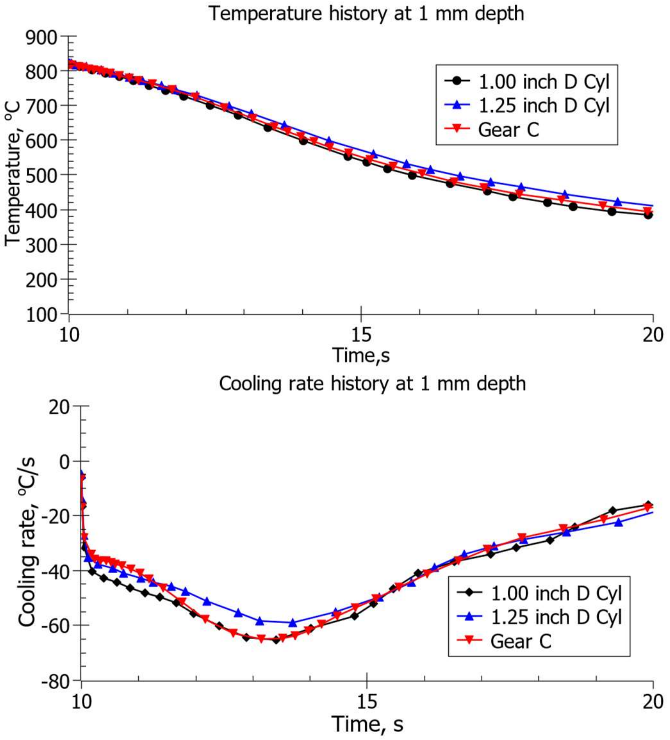

Figure 7: Temperature and Cooling rate history of Gear C at a depth of 1 mm at the mid-flank location and 1.00 inch and 1.25-inch dia test pieces at the mid-height location

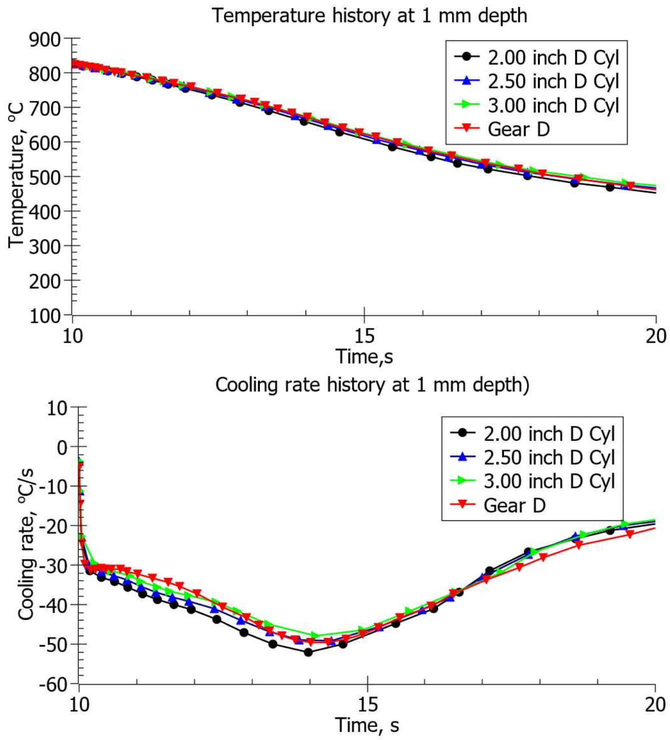

Figure 8: Temperature and Cooling rate history of Gear D at a depth of 1 mm at the mid-flank location and 2.00-inch, 2.50-inch and 3.00-inch dia test pieces at the mid-height location

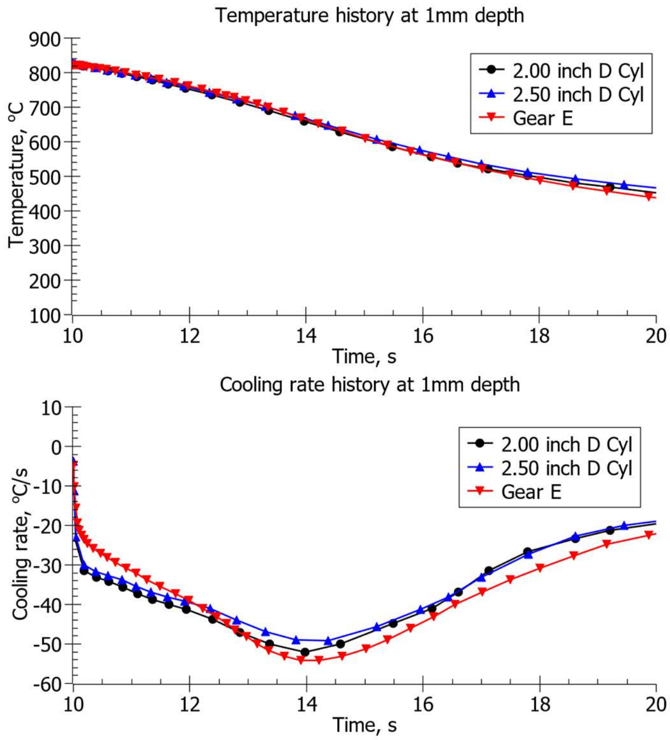

Figure 9: Temperature and Cooling rate history of Gear E at a depth of 1 mm at the mid-flank location and 1.50 inch and 2.00-inch dia test pieces at the mid-height location

Table -4 Characteristic length of gears used for the simulation.

Gear #	Module	CL = ($V_{gear}/A_{tooth\ surf}$)	Test piece dia, inch (mm)	AGMA recom. Test piece dia, mm
A	5.08	9.74	0.85 (21.59)	30.48
B	5.6	13.32	1.25 (31.75)	33.60
C	6.8096	12.26	1.00 (25.40)	40.85
D	8.7588	16.77	2.50 (63.50)	52.55
E	7.9749	18.52	2.00 (50.80)	47.84
F	13.21054	21.78	3.00 (75.00)	79.26

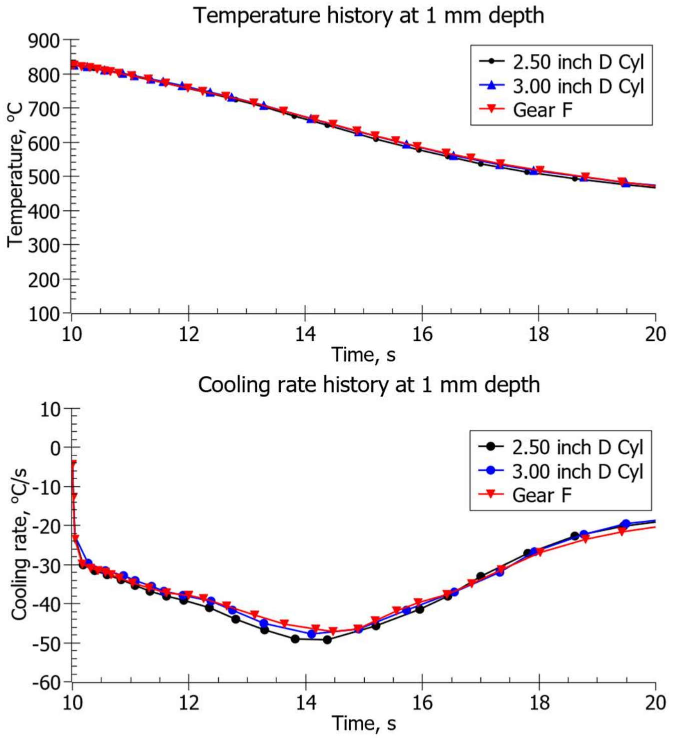

Figure 10: Temperature and Cooling rate history of Gear F at a depth of 1 mm at the mid-flank location and 2.50 inch and 3.00-inch dia test pieces at the mid-height location

Characteristic length (CL) of gears (estimated as the volume of the gear excluding the shaft divided by the tooth surface area exposed for cooling) along with gear module, test piece size estimated using simulation and AGMA recommended test piece size are presented in Table 2. ISO recommends 3 times module for test piece dia., on the other hand, AGMA recommends 6 times of module. The module of gears vs. the corresponding test piece diameter estimated based on the cooling history at a depth of 1 mm in the flank area of the tooth does not follow the guidelines provided by the ISO and AGMA, as shown in Figure 11. This may be due to the overall shape and size of the gear. Most of the gears used in this study are bevel gears where the gear tooth continuously changes its shape, diameter, and orientation. That is influencing the cooling history even at a depth of 1 mm. Additionally, many are pinions with no internal bore, so the volume is relatively large versus the tooth surface area. Figure 11 shows that looking only at the module of the gear is not sufficient for getting a good correlation for all gears.

It also shows that for these larger gears, the AGMA approach is superior to the ISO approach.

To identify the relationship between the proper section size of the test piece and the gear, the characteristic lengths of gears vs. test pieces are plotted in Figure 12. Ideally, the relation between these two parameters should be 1:1, but in the current study, the characteristic length of the test piece is smaller than the CL of gears. The core of the gear likely has a low impact on the cooling history at a depth of 1 mm in the flank area. So, the volume of the gear used in the CL estimation is higher than the effective volume to be used for the calculation. With the exception of Gear, A, all of the gears analyzed in this study were of a pinion type containing no bore. Spur gears with a bore and small volume rim will come much closer to matching cooling curves with a test piece at the same characteristic length (lie on the 45-degree line).

There is an opportunity to establish this characteristic length relationship to test piece diameter (and characteristic length) for a given set of similar shaped gears. This set of gears shows a good relationship for bevel pinions with no bore and for gears with thick rims.

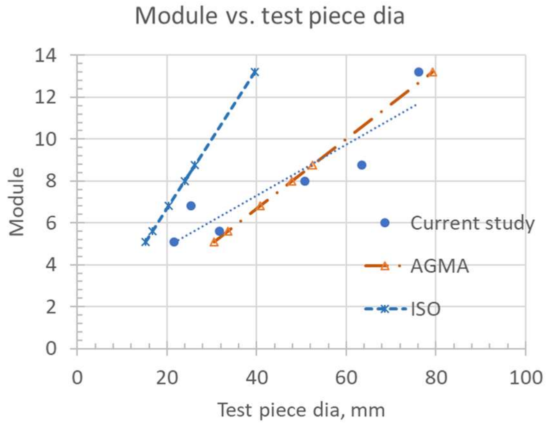

Figure 11: Module of gear vs. test piece diameter

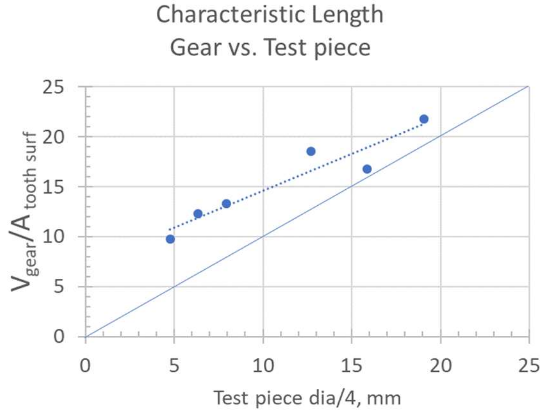

Figure 12: Characteristic length of gear vs test piece diameter. A strong correlation exists between the characteristic length of gears and the test piece.

Conclusion and Recommendation

The proper section size of a test piece can provide enough metallurgical quality information for the gear carburize heat treatment process without sectioning the actual gear, which is expensive and sometimes is not possible. This study focused on identifying the proper section size of the test piece as a function of the gear module or other gear parameters. The following conclusions were made:

1) It has been observed that module size does not correlate well with the test piece diameter that produces the same cooling curve on the gear as it does on the test piece at 1mm depth according to FEA simulation.
2) The AGMA guidance on test piece size is better than the ISO guidance for large gears.
3) The characteristic length of the gear is a good indicator of selecting the proper section size and diameter of the test piece, but this method requires some consideration as to the true effect of the "rim volume" that slows cooling on the mid-flank near surface region. For solid pinions where no bore is present, the regression curve shown in Figure 12 will be excellent guidance for determining the correct test piece size without performing further simulations. For spur gears with bores and thin rims, a different regression curve can be created but it will likely be closer to the characteristic values for the cylindrical test pieces.

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