

# Investigation of hardness behavior after carburizing and hardening of 15CrNi6 steel

*Arsenis Dragatsis<sup>1</sup>, Leonidas Fragkos-Livanios<sup>2</sup>, Dimitris G. Papageorgiou<sup>1</sup>, and Carmen Medrea<sup>1\*</sup>*

<sup>1</sup>Department of Mechanical Engineering, University of West Attica, 250 Thivon & Petrou Ralli Ave. 12244 Egaleo, Greece

<sup>2</sup>Department of Electrical and Electronics Engineering, University of West Attica, 250 Thivon & Petrou Ralli Ave. 12244 Egaleo, Greece

**Abstract.** DIN 15CrNi6 is the most representative grade of the case-hardened steels. The present work analyses the influence of carburizing time on hardness of the specific steel. Specimens with similar chemical composition were heated at 900°C in liquid carbonaceous media for one, two, three and four hours, correspondingly. Then samples were oil quenched and tempered at 180°C for two hours. Microhardness was measured across the carburized zone and case profiles were acquired. The effective case depth was determined as function of carburizing holding time. Core macro hardness was carried out and the impact of holding time on the substrate hardness was discussed. The optimum case depth was defined and the carburizing parameters determined. The hardness control is critical in case hardening practice and results provide practical information to heat treaters, useful both to control the treatment parameters and to minimize the risk of failure.

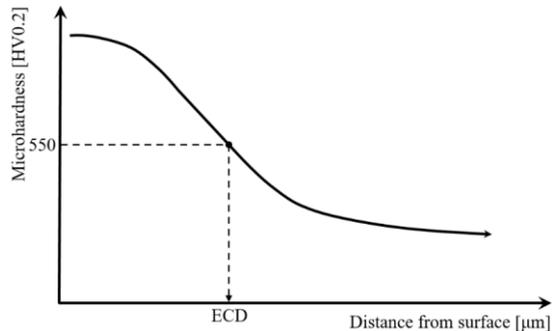
## 1 Introduction

Carburizing is the most common surface engineering procedure. The process involves the diffusion of carbon into the surface of low carbon steels (non-hardenable steels), by exposing them in a carbonaceous environment [1]. A decreasing carbon profile from the surface to the inner of the work is developed. The carbon enriched surface layer (known as the case) has improved hardenability compared with the substrate material (known as the core). Subsequently, the piece is hardened and tempered. The substantially harder surface has improved both wear and fatigue resistance of the part [2], while maintains satisfactory levels of ductility in the core [3, 4]. The contribution of so opposite properties depends on the thickness of the carburized zone and the component geometry. Therefore, the heat treatment sequence requires specific design of any engineering part so to acquire the proper case profile. The case depends on the carburizing temperature, the holding time, and the available carbon potential at the surface [5, 6].

The steels are heated for carburizing in the austenitic area, to ensure increased carbon solubility. Common temperatures used lie between 850° and 980°C [7], but specific temperature is selected according to the available equipment (e.g. furnace construction) and lean manufacturing reasons. Carburizing time (holding time) depends on the case depth

desired and the nominated temperature. The holding time decreases for higher temperature exposure. The carbonaceous media can be assured by conventional procedures such as solid [8], liquid [9, 10], gas [11, 12], or ion [13] carburizing, while more contemporary techniques involve vacuum [14], and laser [15, 16] respectively.

Conforming to the standards, the case depth of any hardened component can be expressed by two types; total and effective [17]. The total case depth means the distance where carbon was diffused into the part. It is required in application necessitating thinner case, and where design requirements are not very severe [18]. The effective case depth represents the distance inner from the surface to a definite hardness. They are several techniques to estimate the case depth and the results determined are different [19]. In engineering applications microhardness measurement is the most common method. A number of indentations are carried out from the edge to the inward of the part in order to acquire a hardness profile (Fig. 1). The effective case depth (ECD) is defined as the vertical distance from the surface to the layer hardened to 550HV [20]. ECD is essential for the design safety of critical engineering parts since it is applied in all industry sectors; automotive and aerospace industry, navigation, petroleum production, mining, defence, agriculture [21].



**Fig. 1.** Graphic determination of ECD from the hardness profile.

Consequently, the case depth is a critical characteristic and needs to be determinate. They are some criteria for the selection of the case hardening depth. The table 1 presents some values of case hardening depth for the most common engineering parts carburized on liquid.

**Table 1.** Criteria of the case hardening depth selection for liquid carburizing

Typical application	Case hardening characteristics	Type of loading/precautions	Proposed Hardness
Engineering part [24]	Surface carbon content 0.6-0.8%	Maximum fatigue strength	Surface hardness >700HV
Gear [24, 26]	0.15-0.18 x gear module, mm, rarely CHD >2.0mm	For optimum fatigue life	60-63 HRC
Small gear [27]	0.51-0.64mm	Optimal service life	60-62 HRC
Idler shaft [27]	0,75mm	Bending and torsion fatigue	58-63 HRC
Crankshaft [27]	1.14-1.4mm	Bending and torsion fatigue	60-63 HRC
Valve [27]	0.4-0.5mm	Abrasive wear	60 HRC min
Coupling [27]	0.25-0.4mm	Torsion fatigue	58 HRC
Thin parts [27]	CHD<0.2 x thickness	Through hardening	
Parts subjected to surface loads [26]		CHD=3-4 times the depth of maximum stress	

The effective case depth depends on the case hardenability and consequently, the carbon gradient. For high and medium alloyed case-hardening steels, the carbon content for 550HV

is typically in the range of 0.30% as it is approximately 0.4%C for low-alloy steels. A “rule of thumb” to estimate the effective case depth is to multiply the total case depth by 3/2 [22].

Low temperature baths (carburizing temperature range 845°C-900°C) are best suited to the formation of total case depths of 0.075 to 0.75mm [23]. Most fatigue strength investigations of case hardening steels show that optimum properties are obtained when the surface carbon content is 0.6-0.8% and the surface hardness at least 700HV [24]. Distortion after carburizing and quenching often results in the part dimensions not meeting the specified tolerances. The case depth must therefore be high enough to attain the final specified case of carburizing depth after grinding. Grinding allowance is typically of the order of 0.1-0.2mm and should be added on the predicted dimension [25].

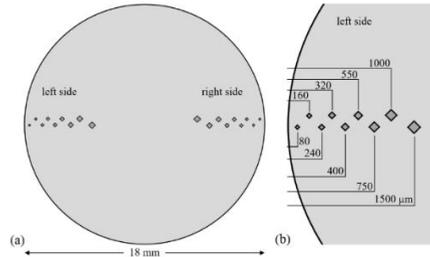
DIN 15CrNi6 is the most representative grade of case hardening steels. It is widely used for small and medium parts. It is a common solution for highly strained parts with good toughness at core as: gears, crown wheels, shafts, various bolts, cutting tools, tools for diverse forming techniques, cold working rolls, measuring tools [28, 29].

A few researches on the steel are available. An attempt was reported to manufacture larger components such as medium and large-sized gears [30]. The further improve of hardness surface by cold working was examined [31]. A failure case was described [32]. Literature review showed a lack of information concerning the heat treatment sequence; which is a matter of each manufacturer and looks to be based more on empirical data.

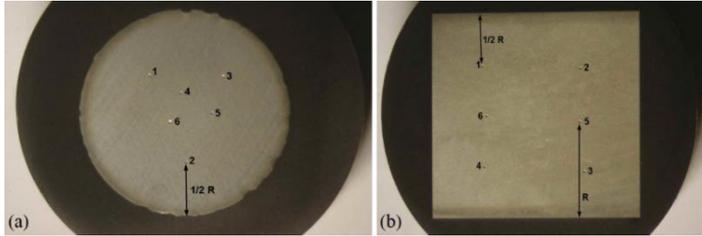
The paper presents the hardness behaviour after carburizing and hardening of the 15CrNi6 steel. The investigation focuses on the influence of the carburizing time on the hardness distribution if a usual heat treatment sequence is applied. The hardness control is critical in case hardening, mainly for relatively small pieces as well as for components with unequal shape. Such parts risk being totally or partially hardened up to the core; then become excessive hard and therefore, prone to cracks. Moreover, the ECD is verified through experimental samples of the steel as the specific technique is destructive and can be applied on the engineering parts. The results of the present work fill the lack of relevant references. Furthermore, they provide practical information to heat treaters, useful both to manage the treatment parameters for specific case hardening, and to minimize the risk of failure.

## 2 Experimental details

Hot rolled bars of 15CrNi6 steel were received in annealed conditions. Cylindrical rods of 18 mm in diameter were cut by using a lathe. The acquired specimens were numbered and randomized using MINITAB 17. The chemical composition of the steel was verified on the samples. An optical emission spectrometer was used. Four sets of four rods were carburized, hardened and tempered to a heat treatment shop. The pieces were exposed in liquid carbonaceous media. It was selected due to its wide use to engineering parts with intermediate dimensional requirements. The carburizing temperature used in the experiment was adopted by the procedure which is already applied in the field. All the other heat treatment parameters except carburizing time were held constant. The holding time is ranging between one to four hours. The effect of the carburizing duration on the steel hardness was examined and quantified. Two specimens were cut on cross section from each rod; one of them was further cut on the longitudinal area. Microhardness (HV0.2) was measured on the carburized zone [33]. Measurements on the opposite sides of the diameter in each specimen were taken to check the homogeneity of the case (Fig. 2a). Fig 2b shows the distances of the prints from the sample edge. The first measurement was taken at 80µm from the edge and was considered as the hardness of the surface. The case profiles acquired were based on the average hardness values. The effective case depth was calculated as function of the carburizing time. Core hardness (HV30) was carried out both on the centre and half radius of the samples (Fig. 3). The impact of carburizing time on the hardness of the substrate was analysed.



**Fig. 2.** (a) Sketch showing case microhardness measurements points, (b) Detail showing the distance between the prints.

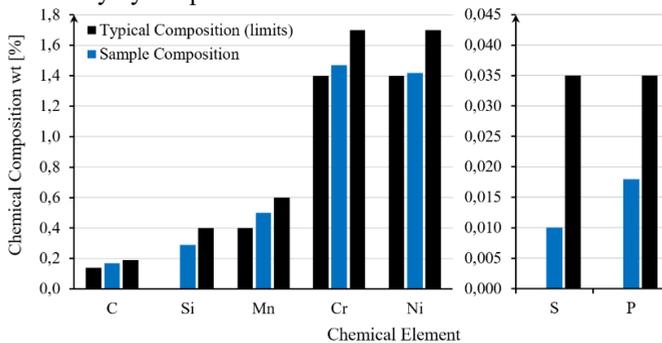


**Fig. 3.** Hardness measurements points on the cross (a) and longitudinal (b) section of the samples.

The Vickers values were converted to Rockwell C, as it is commonly used and is better understood in industrial applications [34]. The carburizing parameters were defined, and the appropriate case depth was discussed.

### 3 Results and Discussion

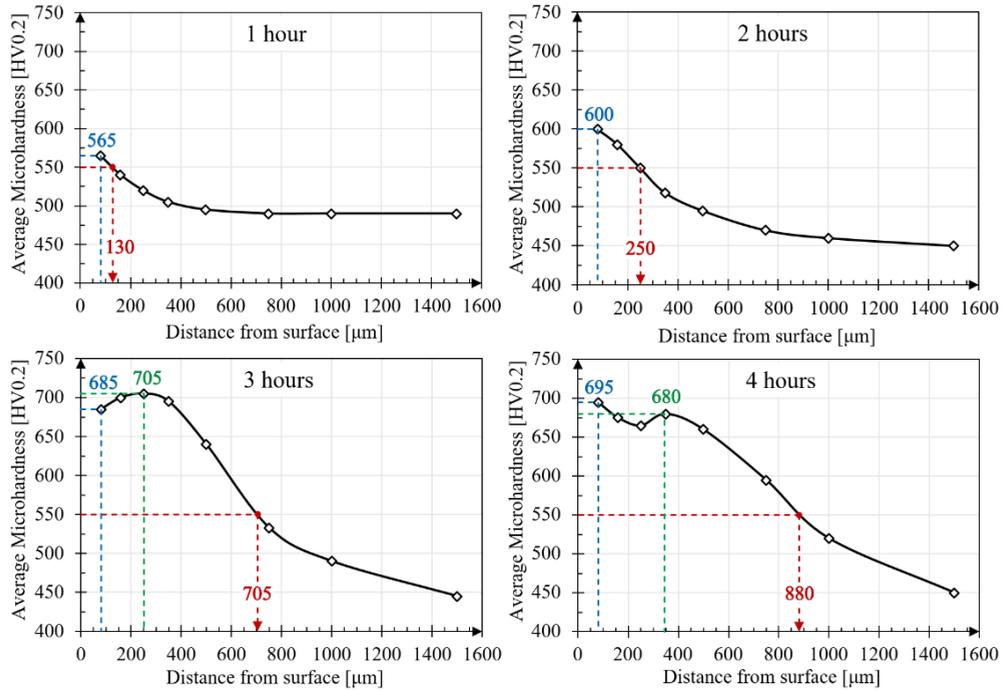
It was observed that the hardness resulted after implementing identical heat treatment sequences is highly dependent on the chemical composition of the steel. Small variations of the ingredient's percentage, although between the limits determined by the standards, lead to diversified results. Consequently, it is very important to ensure that all specimens have the same chemical composition. For this reason, the chemical composition of some randomized specimens was examined. Figure 4 shows the steel's composition in the as-delivered condition [35] and the limits provided by standard [36]. The results confirmed that all received material originates from the same batch, so the steel's post-heat treatment hardness will be affected only by the process.



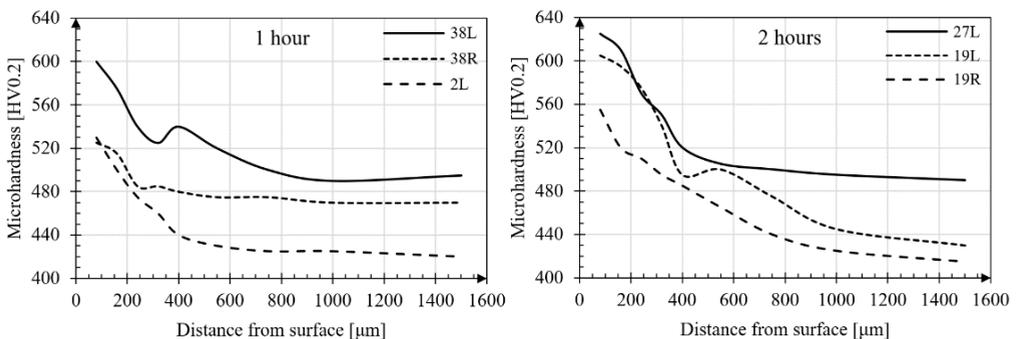
**Fig. 4.** Chemical composition of the 15CrNi6 steel compared to the standard limits [36].

All samples were preheated at 650°C until equalization, carburized at 900°C, cooled to 840°C for 25 min., oil quenched, tempered at 180°C for 2 hours, and finally cooled on air at room temperature. Carburizing duration was 1 hour, 2 hours, 3 hours, and 4 hours, respectively [37]. All other parameters of the treatment sequence were kept constant [38].

Microhardness measurements carried out to the case, resulted on the hardness profile shown on the Figure 5. Generally, the surface case hardness, the effective and total case depth is continuously increase with carburizing time, as expected. By direct quenching the steel surface can be hardened to 43+4HRC [36]. One-hour carburization already increased the average surface hardness to 53,2HRC (565HV). Unfortunately, a wide sample-to-sample variation of the carburizing case was detected, and the specific holding time is considered insufficient (Fig. 6a). The ECD was estimated to 130 $\mu$ m. Nevertheless, it is not applicable due to the inhomogeneous carburization.



**Fig. 5.** Hardness profile of 15CrNi6 steel for different carburization times: (a) One hour, (b) Two hours, (c) Three hours, (d) Four hours.



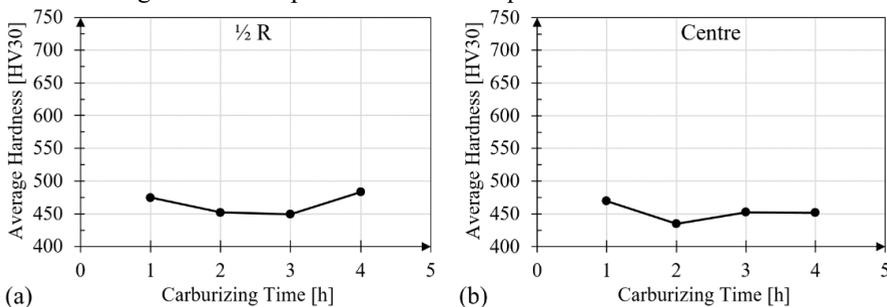
**Fig. 6.** Hardness profiles of randomized samples carburized for one hour (a) and two hours (b) showing hardness dispersion due to inhomogeneous carburization.

The mean hardness on the surface of the samples which were carburized for three hours increased to approximately 59,4HRC (685 HV) and providing uniform surface layer. Inside the case, the hardness is further increased to values that assure high wear resistance [27]. A pick of 60,3HRC (705HV) was detected at a depth of 250 $\mu$ m. Similar slight fluctuation was

reported in case hardening of steels due to hardenability decrease effect of Cr and Mn as carbon content is higher than 0.5%C [39]. The ECD increased to 705 $\mu$ m that usually provides to the case hardening steel high fatigue resistance [24]. Three hours of carburization is considered the adequate duration for the formation of a satisfactory layer of carburization at a temperature of 900°C [26].

The samples carburized four hours was hardened to 59,4HRC (695 HV). They reached a maximum of 59 HRC (680 HV) in 340 $\mu$ m. Similar pattern was previously reported in another case hardening research [40]. The average effective depth was estimated to 880 $\mu$ m, and the case can be characterized as deep [26]. Practically, due to heat transfer and mass phenomena which affecting carburizing, the results can be useful in cases of carburizing cylindrical engineering components with maximum diameter of 28 mm approximately.

The hardness distribution of the core as function of carburization time is depicted in Figure 7. Both centre and half radius depth present the same trend. The minimum average hardness was measured on the centre of the samples which exposed for two hours at 900°C (44,0 HRC, corresponding to 434 HV), while the maximum was found at half of the radius of samples carburized for four hours, respectively (47,9 HRC, corresponding to 483 HV). The average hardness of the substrate was found 45,4 HRC (452 HV) in the centre and 46,6 HRC (465 HV) at half the radius. According to the hardenability chart, the hardness range of the centre can be 37 $\pm$ 5 HRC and 42 $\pm$ 4 HRC to the half radius, respectively [36]. The hardness of the centre as function of the carburizing time is higher compared to the hardenability chart probably provoked by the carburizing process. The hardness behaviour on half radius as function of the carburizing time lies in the predicted limits. Furthermore, considering that most of the case hardening steels exhibit high ductility when have been hardened to 45 $\pm$ 3HRC [39] it could be affirmed that the substrate properties were not affected by the carburizing time of the specific treatment sequence.



**Fig. 7.** Hardness distribution on the substrate of the steel, as function of carburization time: (a) At half of the radius, (b) on the centre of the sample.

## 4 Conclusions

The analyses of hardness behaviour as function of the carburizing time resulted in the construction of a case profile and allowed the measurement of the effective case depth. Investigation showed that carburizing until two-hour exposure at 900°C, in liquid carbonaceous media, resulted in poor and inhomogeneous case. Possible reasons of shallow case and lower hardness of the case is related with the diffusion rate at the selected carburizing temperature. By carburizing the steel for three and four hours conducted to homogenous carburizing, with increased surface hardness, which could improve the wear resistance to the parts. The effective case depth was measured at 705 $\mu$ m, and 880  $\mu$ m, respectively which is adequate in improving the fatigue behavior of the parts as well. The hardness distribution along the case is progressively decreased as the carburizing holding time is increasing attributed to the carbon layer gradually developed due to the diffusion

mechanism. Four hours exposure conducted to a deeper case; specific results could be considered for slight larger parts. Investigation showed that the carburization holding times until 4h did not affect the steel substrate as far as hardness is concerned. In all cases, the substrate hardness is close to the limits of the steel hardenability chart suggesting that the ductility was not affected. The acquired information of the present work helps designer to select the optimum carburizing parameters for the predicted ECD according to the dimensions and shape of the part and to desired mechanical properties.

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