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# The Effect of Cold Forming on Structure and Properties of 32 CDV 13 Steel by Radial Forging Process

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The present study focuses on the effect of various degrees of plastic deformation generated by cold radial forging on the mechanical properties and the fracture morphology of 32 CDV 13 steel. The cold forging percentage was evaluated for 17.45, 33.30, 42.0 and 46.47 %. The microstructural analysis of the steel shows tempered martensite. The tensile strength, yield strength and hardness were found to increase with the increase of cold forging percentage due to the energy stored in the material during cold forging. For higher cold forging percentage, the toughness of the material was decreased according to the reduction of absorbed energy obtained during deformation. Fractography of the Charpy impact specimens shows a surface roughness and dimple pattern for the steel as was acquired and for 17.45 and 33.3 % of cold forging; while for 42 and 46.47 % of cold forging a cleavage fracture pattern was observed.

**Keywords:** *radial forging, cold forging, 32 CDV 13 steel, fractography*

## 1. Introduction

Metal forming should be capable of adding three functions to the products formed: better geometrical precision, better surface quality and better mechanical property products. The increasing demand for the simultaneous generation of the geometry, surface and mechanical properties in cold forging can be observed in metal-forming research in the last decade[1]. Creep-resisting steels containing vanadium have been used throughout the second half of the 20$^{th}$ century as an economic alternative to the more highly alloyed types. The Cr-Mo-V types are chromium-molybdenum creep-resisting steels with a range of chromium and molybdenum contents plus the addition of about 0.25 % vanadium as a strong stable carbide former. Fossil-fuelled power stations have taken advantage of a good long-term creep life of 0.5 %Cr, 0.5 %Mo, 0.25 %V and 1.25 %Cr, 1 %Mo, 0.25 %V alloys, particularly in main steam lines, valve chests and turbine castings. More recently, investigation has focused on the higher alloy types, particularly those with 3 %Cr, 1 %Mo, and 0.25 %V in order to give high-temperature creep properties suitable for use in high-hydrogen atmospheres[2]. Chromium which is the major element added in the Cr-Mo-V type steels, affects hardenability and tempering resistance; the higher the chromium content, the better the hardenability and the better the resistance to softening during tempering. Vanadium, also an alloying element added to the Cr-Mo-V steels, actually reduces hardenability. This effect is related to the very strong carbide-forming ability of vanadium and to the fact that at low austenizing temperatures, around 800 °C, it doesn't dissolve. Finely dispersed vanadium carbide particles thus maintain a very fine austenitic grain size, which reduces hardenability. The strong carbide-forming characteristics of vanadium and the associated fine austenitic grain sizes, however, are desirable because they increase fracture resistance and resist grain coarsening during overheating[3]. The mechanical properties and the fracture morphology of NiCrMoV steel were obtained with a specific composition at different tempered conditions[4]. They found a ductile fracture mechanism for the tempered range studied from 200 to 600 °C, with no evidence of tempered martensite embrittlement. A processing approach for the production of direct-cooled forging steels was studied[5]. They concluded that in order to improve toughness, the use of direct-cooled microalloyed forging steels have evolved from precipitation strengthened ferrite-pearlite steels, to steels with non-traditional bainitic microstructures that may contain a significant amount of retained austenite. Later, the same authors presented a strategy for use of microalloyed steels in long products, including bar and forging steels based on alloying and processing characteristics for this type of steel[6]. The effects of thermomechanical processing parameters on W500 tool steel were determined, considering the radial forging multi step bars along with upsetting wedge specimens[7]. They found that with an increase in strain,

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the mechanical properties were improved and the related optimal values were attained at a critical strain. Radial forging is a hot or cold forging process utilizing two or more radially moving anvils or dies, for producing solid or tubular components. This process is usually used for reducing the diameters of ingots and bars, forging of steeped shafts and axels, forging of riffle barrels and for production of tubular components with and without internal profiles. Deformation in radial forging was obtained for a large number of short-stroke side-pressing operations, performed by four forging tools, located circumferentially around the workpiece[8]. Due to opposing motion of the hammers, no force is transmitted into the machine base. On the radial forging machine there are one or two chuck-heads for holding the workpiece in the proper position and for feeding the dies. In order to obtain round forged workpieces and better finished surfaces, the workpiece rotates during the interval between successive strokes. The rotating chuck-heads stop during the inward motion of the forging dies to prevent the work piece from twisting. Often a mandrel is used inside a tubular workpiece to create internal profile and/or size the internal diameter[9]. The effect of cold forging on the mechanical properties and fracture morphology evolution for the 32 CDV 13 steel has not been determined yet. The objective of the present work is to find an appropriate relationship between the yield strength and toughness for this microalloyed steel with different cold percentages deformation by radial forging.

## 2. Experimental Procedure

### 2.1. *Cold forging*

The material used in this work was Cr-Mo-V type steel, known as 32 CDV 13 according with AFNOR NF, with chemical composition as shown in Table 1. The steel was supplied in quenching and tempering condition, in steel bars of 250 mm in length and 36.5 mm in diameter and machined with a conical shape in the area that have contact with hammers. The bars were cold forged in a radial forging machine with four forging hammers with dimensions as shown in Figure 1. The cold forging percentage was evaluated for 17.45, 33.30, 42.0 and 46.47 % with the experimental parameters shown in Table 2.

### 2.2. *Mechanical properties*

The surface regions deformed by the strokes during cold radial forging process were mechanically removed and samples were obtained of central region of the bar by machining in the longitudinal direction for tension, Rockwell C hardness and impact testing. The size and geometry of the specimens were in accordance with specifications of ASTM E8 and ASTM E23 for the tension and impact testing, respectively. Tensile testing was carried out at room temperature using a universal testing machine Shimadzu of 100 KN with 10 mm/min cross-head speed. The toughness was characterized by the absorbed fracture

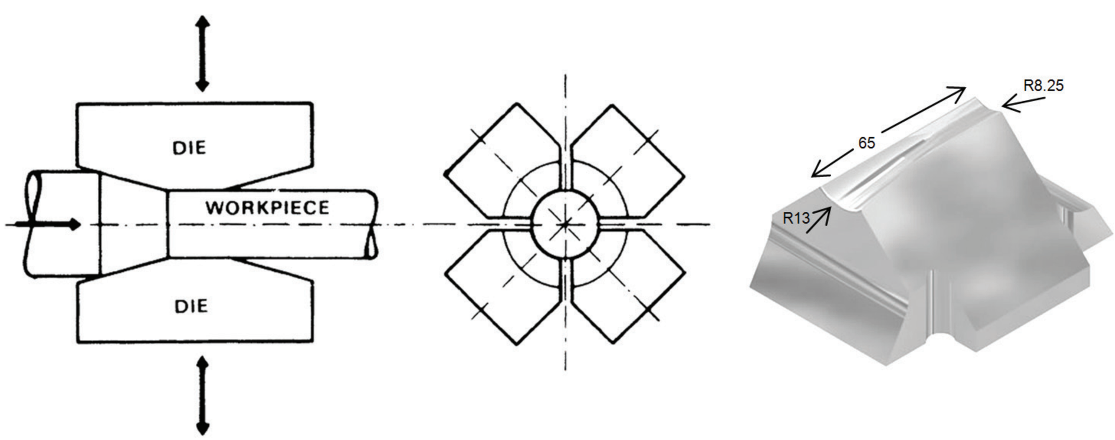



**Figure 1.** Schematic operation of radial forging machine and die dimensions (mm).

**Table 1.** Chemical composition of the 32CDV 13 steel.

| Element | wt. % |
|---|---|
| C | 0.33 |
| Mn | 0.44 |
| Si | 0.15 |
| P | 0 |
| S | 0.02 |
| Cr | 2.87 |
| V | 0.29 |
| Mo | 0.80 |

**Table 2.** Experimental parameters in radial forging.

| Parameter | Value |
|---|---|
| Rotating chuck | 52 rpm |
| Stroke forward | 80 mm $min^{-1}$ |
| Strokes per minute | 1000 |
| Load | 120 Ton |
| Forging percentage | 17.45, 33.3, 42.0, 46.47 % |

energy of Charpy type specimens at ambient temperature. Three specimens from each cold forging percentage were tested for impact and tension tests using an impact testing machine Otto Wolpert-Werke, model PW30/15K. The Rockwell C hardness measurements were carried out on specimens of 25 mm in thickness in the cross direction using a Wilson durometer series 500 in accordance with the standard specification of ASTM E18.

### 2.3. *Microstructural characterization*

In terms of microstructural examinations, standard metallography was employed using an optical microscope Olympus PMG-3 model. A Scanning Electron Microscope (JEOL JSM-6490LV) was used to observe cold forged samples and fracture surfaces of Charpy specimens. The effect of the cold forging percentage was observed on the surface, middle and center of the steel bar in the transverse direction. Expansion lateral measurements were carried out on fracture surfaces of Charpy specimens in accordance with ASTM E23. The measurement was performed using a microscope for metrology Carl Zeiss series J831 (resolution 0.001 mm), discarding the burr of the specimens.

## 3. Results

### 3.1. *Cold forging*

The microstructure of 32 CDV 13 steel as was acquired is shown in Figure 2, in which tempered martensite can be observed. The microstructures of the cold forged test samples are present for 17.45, 33.30 and 47.46 % of cold forging and were carried out on the surface, middle and center of the steel bar. The metallurgical inspection at the bar surface, where severe cold forging was applied to the test sample due to direct striking with hammers, is observed in Figure 3. A sound microstructure constituted by tempered martensite and linear flow patterns in the transverse direction were observed for the three cold deformation percentages that were evaluated. The results for the intermediate and center zone of the steel bar were very similar, both show tempered martensite, and only the results for the center bar are presented in Figure 4.

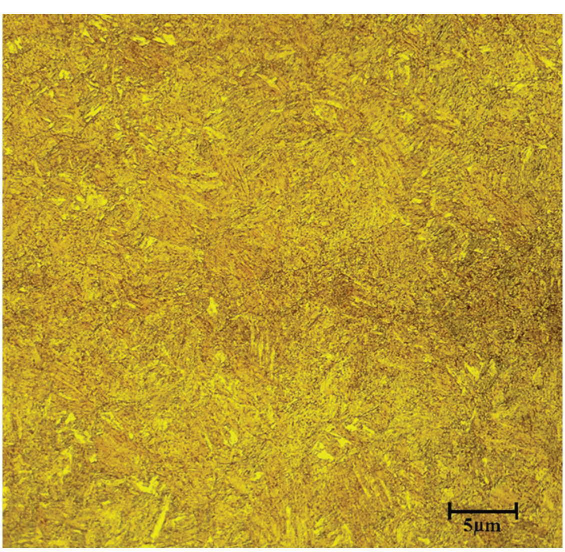



**Figure 2.** Optical micrograph of 32CDV 13 steel as was acquired showing tempered martensite.

### 3.2. *Tension test*

Tension tests were carried out for three specimens of each percentage of cold forging, including an undeformed specimen. Typical strain-stress curves were obtained, when the percentage of cold forging was increased, the strength of this steel increased too. The average stress results are shown in Table 3 for the cold forging percentages assessed. The variation of yield strength and tensile strength with the percentage of cold reduction is shown in Figure 5. The results indicate that cold forging substantially increases the yield and tensile strength of the 32 CDV 13 steel by about the same rate.

### 3.3. *Rockwell C hardness*

The effect of the percentage of cold forging on the Rockwell C hardness is shown in Figure 6. Each point in Figure 6 represents an average of 10 measurements on the forging plane along the forging direction. The increase of the percentage of cold deformation increases slightly the hardness values. The ratio of the average tensile strength in MPa to the average Rockwell C is about 35.8 for all samples evaluated, as is observed in Table 3.

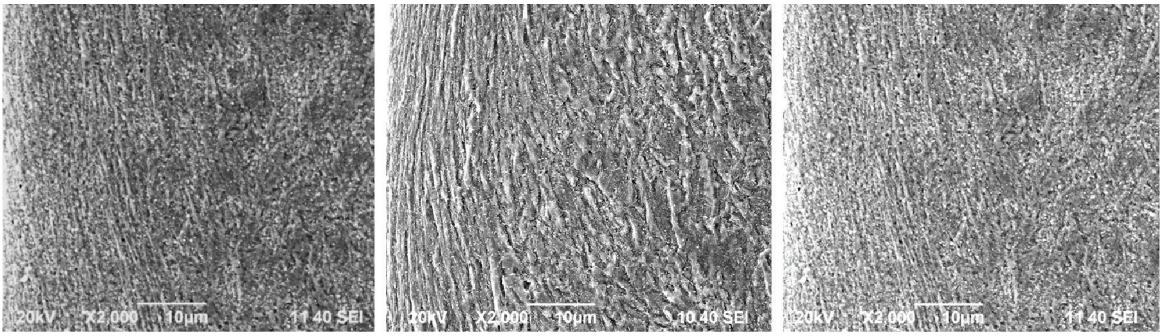
### 3.4. *Fracture behavior*

The effect of the percentage of cold forging on impact energy absorption at room temperature was carried out and the results are shown in Table 3 and Figure 7. It must be noticed, the high capacity of energy absorption of this type steel. It is observed that toughness improves by increasing the cold forging until it reaches 33.3 %; whereas for the 42 % and 46.47 % of the cold forging, the toughness decreases significantly. Fractography of the charpy impact specimens are shown in Figure 8 for the steel as was acquired and to 33.3 % and 46.47 % of cold forging. The fracture features of the samples without deformation and cold forged to 33.3 and 46.47 % are shown in Figure 9. It can be seen that the shear area (S region) in Figure 9a is bigger than samples cold forged (Figures 9b, c). The lateral expansion measurement is shown in Table 4.

## 4. Discussion

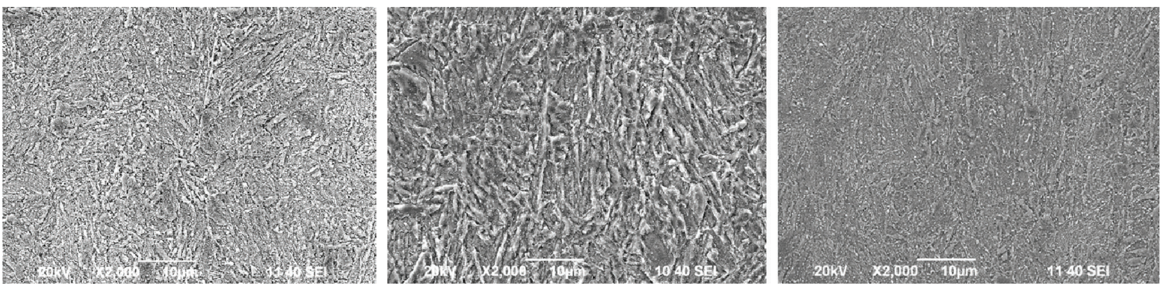
### 4.1. *Cold forging*

In contrast with the surface bar, for the middle and center zones, it is not longer clearly an orientation pattern of the microstructure with cold deformation. During deformation, mechanical integrity and consistency are maintained along the grain boundaries, this means that grain boundaries are not separated and there is only distortion by plastic deformation in the direction where strain is applied. The stress required to deform the metal was increased when the percentage of cold forging was increased, due to the




(a) (b) (c)

**Figure 3.** Tempered martensite of the surface bar in the transverse direction after cold forging to a) 17 %, b) 33 % and c) 46.47 %.




(a) (b) (c)

**Figure 4.** Tempered martensite of the center bar in the transverse direction after cold forging to a) 17 %, b) 33 % and c) 46.47 %.

**Table 3.** Variation of average yield and tensile strengths, hardness and impact energy with forging percentage for 32CDV 13 steel.

| Forging (%) | Tensile Strenght, $T_S$ (Mpa) | Yield strenght, $Y_S$ (MPa) | Rockwell hardness, HRC | $Y_S/T_S$ | $T_S$/HRC | Impact energy (J) |
|---|---|---|---|---|---|---|
| 0 | 1012.6 | 998.04 | 30.5 | 0.98 | 33.2 | 150.23 |
| 17.45 | 1115.58 | 1098.41 | 31.3 | 0.98 | 35.6 | 176.26 |
| 33.30 | 1168.54 | 1153.82 | 32.6 | 0.98 | 35.8 | 185.34 |
| 42.0 | 1242.41 | 1226.67 | 33.5 | 0.98 | 37.0 | 148.27 |
| 46.47 | 1259.92 | 1247.33 | 33.7 | 0.99 | 37.3 | 87.93 |

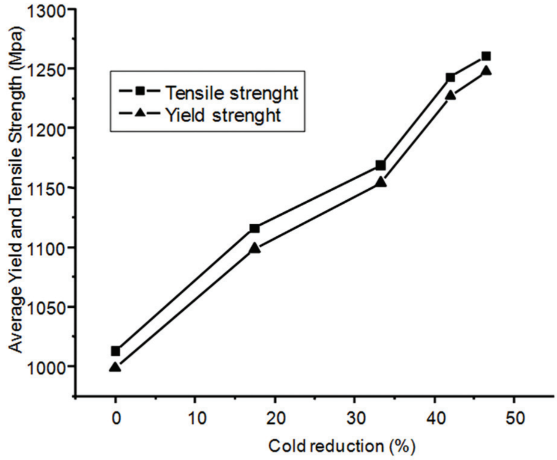



**Figure 5.** Effect of cold forging on the tensile properties of 32CDV 13 steel.

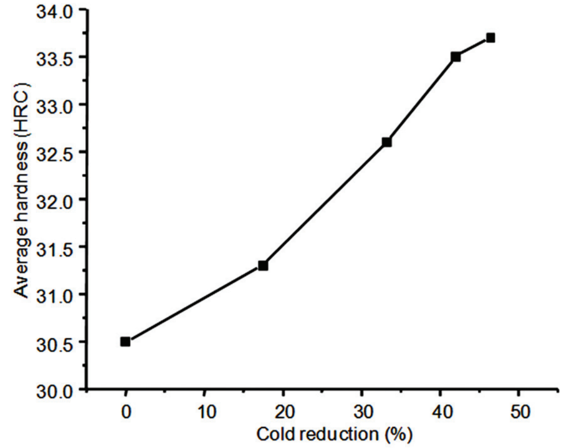



**Figure 6.** Effect of cold forging on the Rockwell C hardness of 32CDV 13 steel.

formation of a high amount of dislocation which avoids deformation.

### 4.2. *Tension test*

Figure 5 shows that the gap between the yield strength and tensile strength curve becomes constant in 0.98 as the percentage of cold forging was increased, as shown by tensile strength- yield strength ratio in Table 3. The increase of the yield and tensile strength is due to the energy stored in the material during cold deformation[10]. This behavior may indicate that cold forging has a significantly effect on the yield and tensile strength for this type of steel.

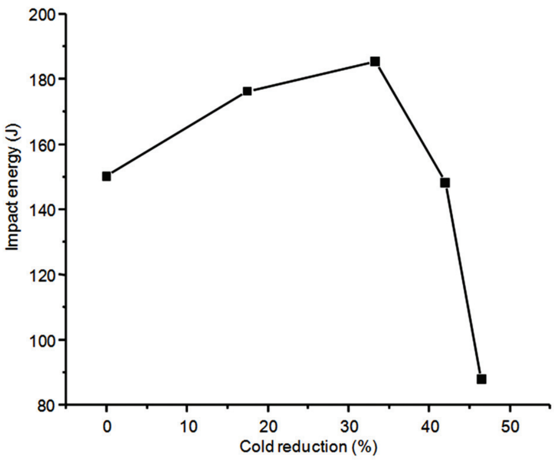


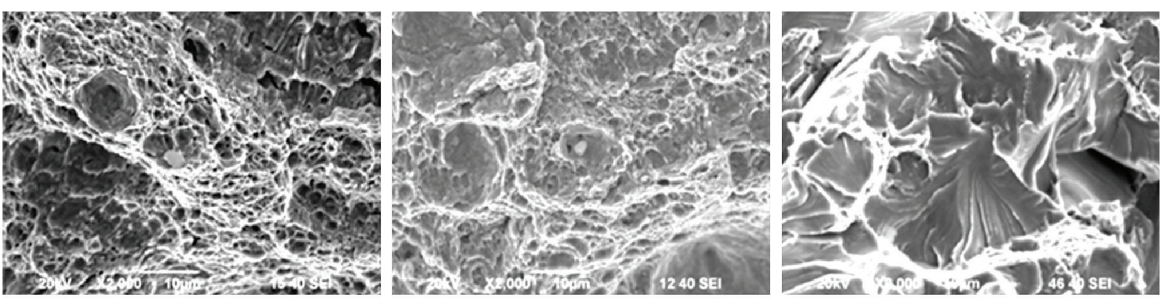

**Figure 7.** Variations on impact energy with different cold forging of 32CDV 13 steel.

### 4.3. *Rockwell C hardness*

According with the results of Figures 5 and 6 and considering that the difference between yield and tensile strength is a measure of the work hardening rate, it can be concluded that increasing the percentage of cold forging results in lower work hardening capacity.

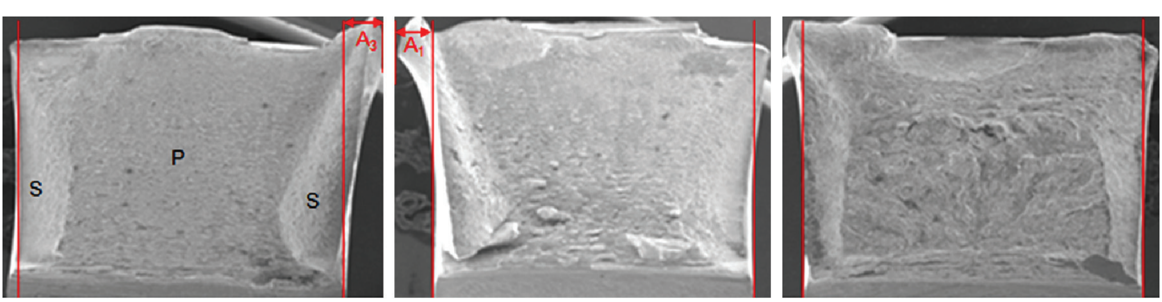
### 4.4. *Fracture behavior*

The toughness reduction in Figure 7 is attributable to the lack of mobility of the grains of the material due to the dislocations that obstruct the movement, which is caused by cold deformation. Figure 8 shows, the dimpled appearance in fibrous zones, which is a characteristic of microvoid coalescence for the material as receiving. The average void size and spacing in fracture surface are smaller for the sample cold forged to 33.3 % than those in the sample without deformation. The presence of dimples indicates a ductile fracture mechanism. However for the higher



(a) (b) (c)

**Figure 8.** SEM fractograph of charpy specimens of the 32CDV steel to a) as was acquired and after cold forging to b) 33.3 % and c) 46.47 %.




(a) (b) (c)

**Figure 9.** Charpy fracture surface of 32CDV 13 steel to a) as was acquired; and after cold forging to b) 33.3 % and c) 46.47 %.

**Table 4.** Variation of average lateral expansion with forging percentage for 32CDV 13 steel.

| Forging (%) | A1 | A2 | A3 | A4 | Lateral expansion (mm) |
|---|---|---|---|---|---|
| 0 | 0.423 | 0.57 | 0.535 | 0.249 | 1.105 |
| 33.3 | 0.609 | 0.614 | 0.347 | 0.327 | 0.961 |
| 46.47 | 0.207 | 0.320 | 0.511 | 0.493 | 0.831 |

percentage of cold forging, the fracture surface changed from dimple to cleavage fracture pattern with river marks, which corresponds to brittle fracture mechanism. For the samples evaluated with different cold forging percentage, the fracture mechanism transforms from ductile to brittle fracture with lower capacity energy absorption. Figure 9 shows an increase in the dimensions of the opposite sides to the notch on the impact specimens. The lateral expansion measurement was decreased when the percentage of cold forged was increased. It has been reported[11,12] that the higher ratio of "S" to "P" areas is an indication of higher ductility.

The chemical composition of the 32 CDV 13 steel helps to obtain a high increase fracture resistance, mainly by the presence of the low contents of impurity elements (P+S) and the chromium, molybdenum and vanadium. Cold forging deformation was clearly observed in the bar surface, in spite of that, the effect of cold deformation acts on the entire mass of steel, as was evident in the tensile and impact results. The effect of cold forging deformation is proportional to the increase of mechanical properties evaluated (hardness, tensile and yield strength) and these are related to plastic deformation. Therefore, as cold forging was increased, the steel becomes more resistant to deformation. The steel toughness was improved for low cold forging, until it reached 33.3 % of cold deformation. However for cold forging deformation higher than 33.3 %, the energy absorbed by the material prior to fracture is much lower than for low cold forging percentage. This means that materials grains are so deformed that they have very little freedom to move and instead of absorbing energy in the deformation, the material becomes brittle and fracture becomes without any deformation, as it was shown by the fractography results. The Charpy fracture surfaces shows that the lateral expansion was reduced when the percentage of cold forging was increased. These measurements represent the energy absorption capacity of the material to deform plastically before fracture occurs; increasing strength and hardness, and decreasing the toughness of the steel.

## 5. Conclusions

The mechanical behavior and the fracture morphology of 32 CDV 13 steel with different cold radial forging percentage at ambient temperature have been studied. The results obtained can be summarized as follows:

- The 32 CDV 13 steel presents tempered martensite to the cold forging deformation evaluated. In spite of the cold forging acts on the entire mass of steel, linear flow patterns were only observed in the bar surface;
- The yield and tensile strengths were found to increase almost at the same rate ($Y_S/T_S = 0.98$) with increasing cold forging percentage;
- The ratio between the average tensile strength and the average Rockwell C hardness was in the range of 33.2 and 37.3;
- The fractography on the Charpy impact specimens indicates a transition mechanism from ductile to brittle fracture for cold forging of 17.45, 33.3 % and 42, 46.47 %, respectively;
- The 32 CDV 13 steel shows a high capacity of energy absorption which increases to low cold forging percentages ($\leq$33.3 %).

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