An experimental analysis of fracture behavior under varied Temperature and material conditions

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***Abstract** - The study discusses the effects of temperature on impact energy, which was carried out on low carbon steels (C40) by varying notch sizes and temperature conditions. The test specimen were subjected to Annealing, Normalizing, Oil quenching, Zinc plating and finally CVN Powder coating and the effects of temperature on impact energy were analyzed. Further the mode-I fracture toughness were analyzed graphically. An optimum condition of temperature and notch size has been proposed for the aerospace applications.*

Key Words:*Toughness, Fracture Strength, CharpyTest Evaluation, Tests*

1.0 INTRODUCTION

The concepts of fracture mechanics are ideas for developing methods of predicting the load carrying capabilities of structures and components containing cracks. Though virtually all design and standard specifications require the definition of tensile properties for a material, these data are only partly indicative of inherent mechanical resistance to failure in service. Except for those situations where gross yielding or highly ductile fracture represents limiting conditions, tensile strength and yield strength are often insufficient requirements for design of failure resistant structures.

The concept of fracture mechanics are concerned with the basic methods for predicting the load carrying capabilities of structures and components containing cracks. The fracture mechanic approach is based on a mathematical description of the characteristics stress field that surrounds any crack in a loaded body. When the region of plastic deformation around a crack is small compared to the size of the cracks, the magnitude of the stress field around the crack is related to the stress field around the crack is related to the stress – intensity factor, K, with:

$$K = \sigma\left(\sqrt{a}\right) Y \left(\frac{a}{W}\right)$$

Where,

σ = remotely applied stress,

a = characteristics flaw size dimension,

Y = geometry factor that depends on the ratio of the crack length, a, to the width, W, determined from linear elastic stress analysis. The stress intensity factor, K, thus represents a single parameters that includes both the effect of the stress applied to a sample and the effect of a crack of a given size in a sample. The stress – intensity factor can have a simple and relation to the applied stress and crack length, or the relation can involve complex geometry factors for complex loading, various configurations of real structural components, or variations in crack shapes. In this way, linear elastic analysis of small scale yielding can be used to define a unique factor, which is proportional to the local crack tip stress field outside the small crack tip plastic zone.

These concept provide a basis for defining a critical stress intensity factor (K_c) for the onset of crack growth, as material property independent of specimen size and geometry for many conditions of loading and environment. In general, when the specimen thickness and the in-plane dimensions near the crack are large enough relative to the size of the plastic zone, the values of K at which growth begins is a constant and generally minimum value called the plane strain fracture toughness factor, K_{IC} of the material. The parameter K_{IC} is a true material property in the same sense as is the yield strength of a material. The plane strain fracture toughness, K_{IC} particularly pertinent in materials selection because, unlike other measures of toughness, it is independent of specimen configuration.

The technology of fracture mechanics has been applied to fatigue crack growth rate assessment under various conditions, environmental and stress corrosion problems, dynamic fracturing, and cryogenic testing temperatures. These developments, which have occurred in the past 35 years, have led to broad use of fracture mechanics and to greater confidence in the design of fracture critical structures.

2.0 LITERATURE SURVEY

Norris, D. M. Reaugh, J. E. et.al [1] in their paper has discussed the effects of fracture –toughness correlation based on charpy initiation energy. They have done the correlation of 23 steels with variations in yield strength of 447 to 1696 MPa, fracture toughness of 40 to 353 kN/m, and Charpy toughness (CVN) of 22 to 192. They have opined that, the CVN^i correlation is better than that obtained by RNB or one based on CVN data alone.

J. M. Barsom and S. T. Rolfe [2] have carried out the correlation between K_{IC} Charpy notch test results in the transition temperature range. They have given the guidance on related aspects such as conversion between fracture toughness parameters, treatment of sub-size charpy data and the considerations necessary for impact loading.

S.T. Rolfe and S.R. Novak [3] have carried out bend K_{IC} Testing of medium strength high toughness steels. They have used Linear-elastic fracture mechanics (LEFM extensively to analyze the fracture behavior of steels having yield strengths greater than 200 psi. Their results indicate that LEFM can be used to analyze the fracture behavior of medium-strength high-toughness steels. They have investigated, K^{Ic}values ranging from 87 to 246 ksi in.

Chaouadi, R. and Fabry, A [4] in their paper have carried out charpy impact test for characterizing the flow and fracture behavior of reactor pressure vessel steels. They have investigated the possibility to estimate the material crack resistance from a single Charpy-V impact test. They arrived at the correlation and proposed the method for the accurate determination of both static as well as dynamic crack resistance from the simple charpy impact test.

3.0 PROBLEM STATEMENT

Based on the literature survey, the paper discusses the fact that the material may fracture in a variety of ways, depending on conditions such as temperature, the stress state and its variations with the time, and the environment in which it functions. The several types of fracture can be characterized broadly according to low temperature tensile fracture, high temperature tensile fracture (creep fracture), fatigue fracture embrittlement and static fatigue. These tests have been carried out to arrive at the optimal values.

The experiment analysis has been carried out on low carbon steel specimens at three different fields' namely material conditions, impact testing and determination of K_{IC} . The specimen which are to be tested are maintained at different material conditions like normal, annealed, oil quenched, zinc plated of varied thickness, and power coated of varied thickness specimens. These specimens are tested in charpy impact testing machine at varied temperatures. Finally based on the result of charpy impact test the fracture toughness i.e., K_{IC} is calculated and graph is plotted for the K_{IC} values.

4.0 EXPERIMENTAL SETUP

Slip in crystal is limited to certain planes and directions, the applied stress required to initiate plastic flow depends on the orientation of the stress relative to the crystallographic axis of crystal. In the plastic deformation of single crystal, the applied tensile stress may be resolved into two components a shear stress in the slip direction on the slip plane, and the stress normal to the slip plane.

Initially the low carbon steel rolled bar stock is cut to a cross section of 10x10x55 mm, a sample size of 100 specimens of U –Notch and 110 specimens of V –Notch were prepared for Charpy impact testing. The specimens were cut as per ASTM E 23 standards. A total of 20 specimens were treated with annealing, 10 specimens with oil quenching. Further 50 specimens of U –Notch and 40 specimens of V-Notches were electroplated with zinc by varying the thickness in the range of 5 to 25 microns with the step of 5 microns. Finally 40 U –Notch specimens and 30 V-Notch specimens were coated with powder coating with spray gun powder coating technique.

The impact testing machine was used for the different specimens with the charpy test setup. Prior to testing a group of specimen and before a specimen is placed in the position to be tested the machine is checked by a free swing of the pendulum. With the indicator at the initial position, a free swing of the pendulum shall indicate zero energy on a machine reading directly in the energy which is compensated for frictional losses.

The specimens were tested for varying temperatures of the specimen starting from 0^0C to 225 ^{0}C in steps of 25^{0}C. To achieve 0^0 c to the specimen, the specimens were kept in a closed vessel which was filled with 10kgs of ice cubes. The specimens were kept in this condition for a period of 5 hours. In order to obtain and maintain the temperature from 25^{0}C to 225 ^{0}C in steps of 25^{0}C, a muffle furnace was used. The 7 segment electronic display unit was used to monitor the temperature. For experimental purposes, a total of 12 specimens were kept in muffle furnace and was switched on. The temperature was set by adjusting the rotating knob of the furnace and setting this condition for a period of 3 to 4 hours to obtain the set temperature. Then the furnace was let at that set constant temperature for about 2 hours. The heated specimen was fixed in the charpy impact testing machine for recording the data. This process was repeated for the remaining sets of specimens. Table 1 shows the number of specimens used for the charpy impact testing.

Table 1: shows the number of specimens used for the charpy impact testing.

Notch Type	Material Condition											
	Normal	Annealed	Oil Quenched	Zinc plated in(µm)					Powder Coated in (µm)			
U- Notch	10	-	-	5	10	15	20	25	70	80	90	100
				10	10	10	10	10	10	10	10	10
V- Notch	10	10	10	-	10	10	10	10	10	10	10	10
Total	20	10	10	10	20	20	20	20	20	20	20	20
Grand Total : 210 (Two hundred and ten only)												

5.0 DATA COLLECTION AND ANALYSIS

Impact testing has been carried out on low carbon steel (C40 steel) specimens under Annealed, Oil Quenched, Zinc Plated and Powder Coated material conditions. These specimens were prepared as per ASTM E23 standards with both U and V Notches. The coatingthickness for zinc plated specimen were maintained at four different levels i.e., 10, 15, 20 and The strength aspect of both zinc plated and powder coated specimen with respect to the varied temperature.Is shown in Table 2 and the corresponding data tables are shown in the Fig.1 with respect to the notch configuration. The Transition Temperature taken for Zinc plated U – Notched Specimen of 20 µm was 125 ºC, Zinc plated V – Notched Specimen of 20 µm was 100 ºC, Powder Coated U –Notched Specimen of 90 µm was 100 ºC and Powder Coated V –Notched Specimen of 90 µm

25µm. In the same way, coating thickness for powder coated specimens was maintained at four different levels, 70, 80, 90 and 100 µm. All the two hundred and ten specimens were impact tested under varied temperature ranging from 0^0C to 225^{0}C in steps of 25^{0}C.

5.1Behaviour of Fracture under varied Temperature

was 100 ºC. It is clear from the graphs that U – Notched specimen will absorb less amount of energy i.e. The strength of the V –Notched specimen is more than that of the U –Notched specimen, as can be seen from the graphs the impact energy will increases as the temperature of the specimen increases. But from certain temperature onwards it will decreases drastically. This particular temperature is called Transition Temperature, where the fracture behaviour changes from Brittle to Ductile fracture

Table 2: Impact test results of the specimens under varied conditions

SL. NO.	MATERIAL CONDITION	TEMPERATURE IN ºC AND IMPACT ENERGY (E_o / A) IN Kgf.m/mm^2									
		0	25	50	75	100	125	150	175	200	225
1	NU	0.018	0.065	0.071	0.073	0.080	0.083	0.085	0.086	0.089	0.096
2	NV	0.007	0.010	0.016	0.018	0.021	0.022	0.025	0.028	0.032	0.030
3	AV	0.201	0.275	0.277	0.290	0.255	0.247	0.245	0.244	0.242	0.192
4	OV	0.181	0.192	0.207	0.283	0.289	0.290	0.285	0.261	0.220	0.217
5	ZU 5	0.002	0.008	0.015	0.020	0.022	0.018	0.017	0.017	0.016	0.016
6	ZU10	0.002	0.008	0.012	0.015	0.024	0.014	0.013	0.013	0.012	0.010
7	ZU15	0.006	0.009	0.013	0.017	0.017	0.029	0.028	0.020	0.015	0.012
8	ZU20	0.010	0.012	0.013	0.014	0.017	0.018	0.017	0.015	0.014	0.012
9	ZU25	0.012	0.014	0.016	0.017	0.015	0.013	0.012	0.012	0.012	0.010
10	ZV10	0.026	0.032	0.047	0.051	0.076	0.053	0.040	0.039	0.037	0.035
11	ZV15	0.023	0.025	0.026	0.047	0.067	0.052	0.040	0.039	0.048	0.035
12	ZV20	0.015	0.018	0.020	0.045	0.063	0.059	0.044	0.042	0.040	0.038
13	ZV25	0.011	0.012	0.015	0.045	0.057	0.060	0.047	0.045	0.045	0.040
14	PU70	0.005	0.008	0.028	0.045	0.070	0.073	0.070	0.061	0.060	0.056
15	PU80	0.004	0.044	0.053	0.070	0.082	0.080	0.072	0.058	0.049	0.048
16	PU90	0.002	0.044	0.048	0.060	0.108	0.075	0.065	0.065	0.063	0.060
17	PU100	0.002	0.009	0.059	0.072	0.085	0.076	0.072	0.063	0.048	0.040
18	PV70	0.014	0.017	0.026	0.063	0.068	0.055	0.050	0.048	0.047	0.040
19	PV80	0.018	0.034	0.047	0.055	0.060	0.055	0.048	0.044	0.041	0.039
20	PV90	0.013	0.020	0.027	0.055	0.063	0.053	0.046	0.043	0.038	0.036
21	PV100	0.010	0.015	0.052	0.046	0.061	0.051	0.047	0.037	0.031	0.029

International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 02 Issue: 08 | Nov-2015 www.irjet.net p-ISSN: 2395-0072

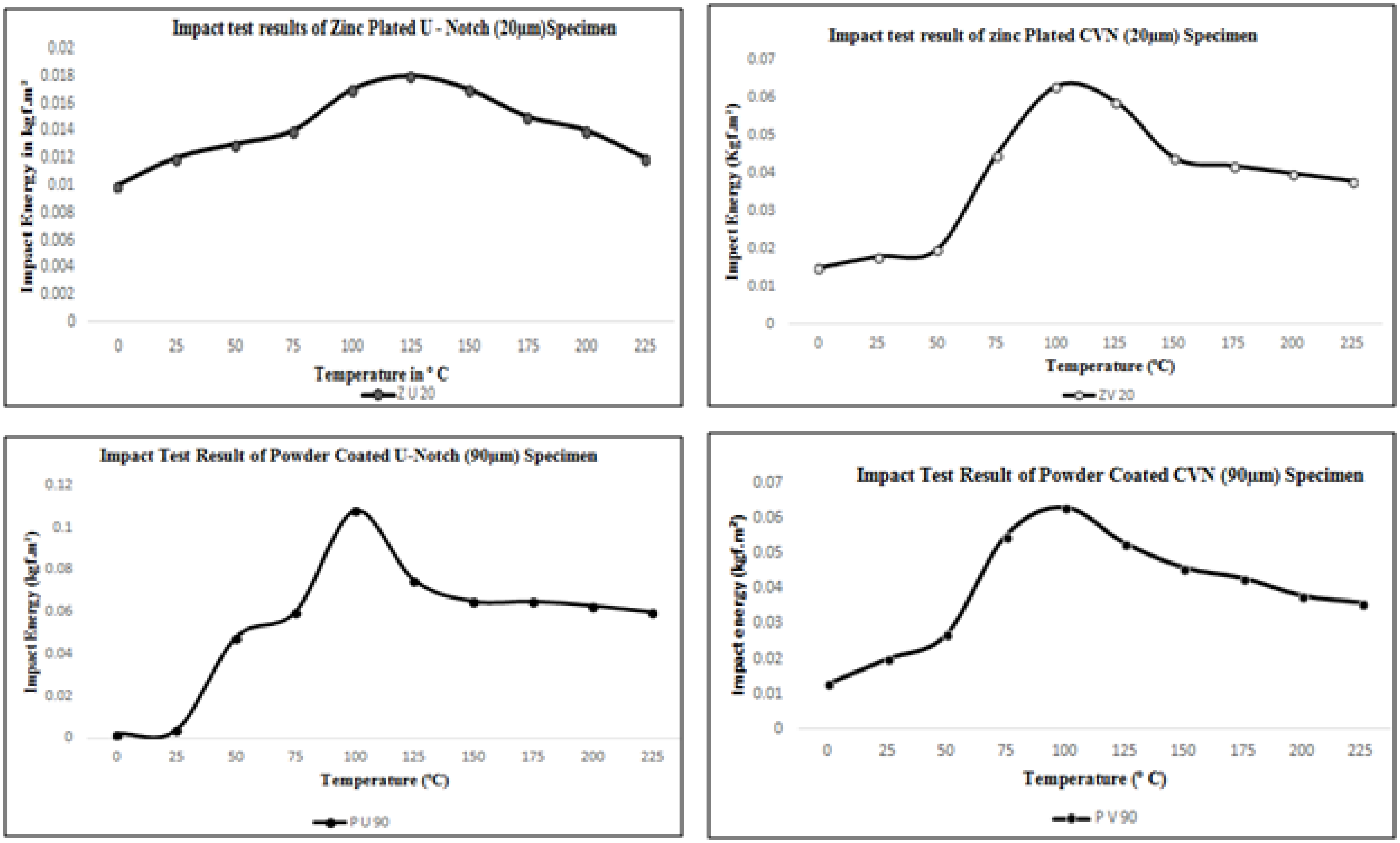

Fig 1: Impact test results of the specimens under varied conditions

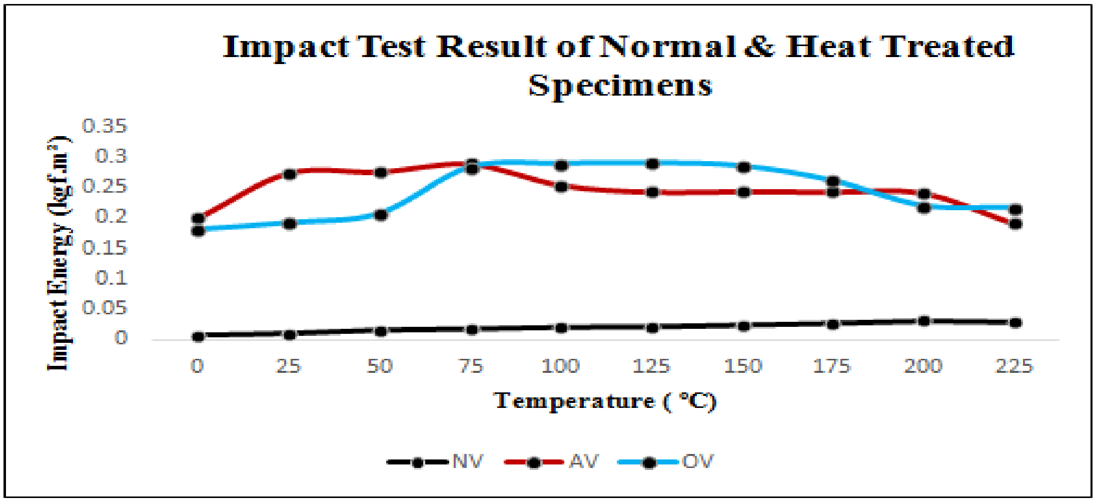

Fig: 2 Impact Test Result of Normal & Heat Treated Specimens

The material under normal conditions can work satisfactorily up to 225ºC and beyond 225 ºC of temperature there will be low level of impact Energy. For the annealed specimens the strength will increase with increase in temperature up to 75ºC beyond which the strength will decrease. In the same way oil quenched specimen can work satisfactorily with maximum strength up to 125ºC only.

5.2 Impact test result of Coated Specimen with Varied Thickness under Varied Temperature

As can be seen from the graphs in fig. 3, the variations in the strength aspects of the coated specimen under varied temperature ranging from 0ºC to 225ºC in steps of 25ºC shows maximum strength when the notch is powder coated with U-Notch of 90µm specimen maintained at 100ºC and minimum strength can be achieved by zinc plated U-Notch of 20µm specimen maintained at 225ºC.

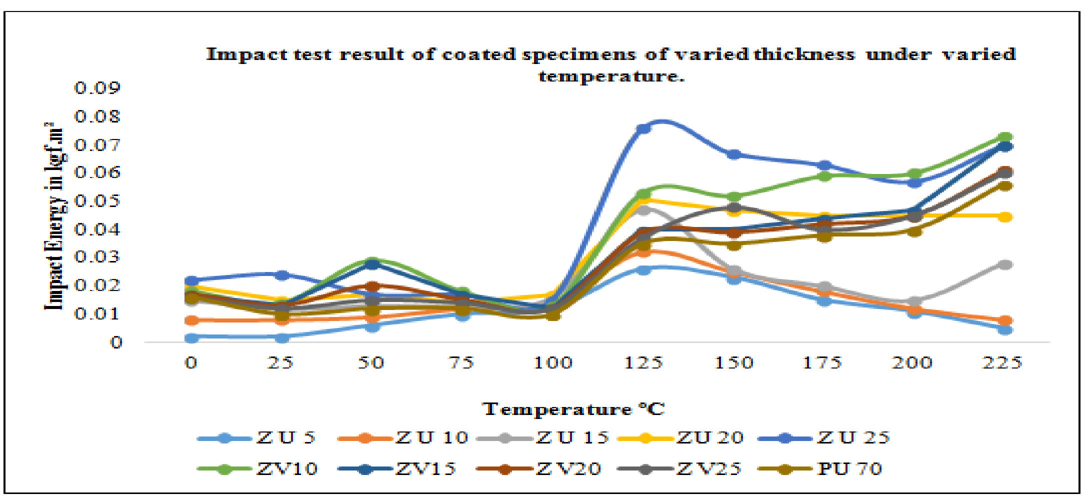

Fig 3: Impact Test Results of Coated Specimen with Varied Thickness & Temperature

5.2 Effect of Temperature and Material Condition on Mode–I Fracture Toughness (K_{IC})

The plain strain fracture toughness for the low carbon steel was determined form the CVN impact energy obtained from the experimentation. The K_{IC} values were calculated from the empirical correlation proposed by Rolfe & Novak. The empirical relation used in the present work is as shown.Fracture Toughness by Novak is given by,

$$K = \sqrt{(5\left(\left(\frac{CVN}{\sigma y}\right)\right) - 0.05))}\ X\ \sigma y$$

The fracture toughness values K_{IC} values for all types of specimen tested under 100ºC is shown in Table 3 and the corresponding graph is shown in Fig 4. As can be seen, at temperature of 100ºC most of the specimens show the transition temperature behaviour.

Table 3: Fracture toughness values obtained by Rolf and Novak K_{IC} Correlation of different material condition at 100˚C Temperature

Material Conditions	Fracture Toughness (K_{IC}) At 100ºc
NV	58.3
AV	220.01
OV	250.03
ZV10	124.71
ZV 15	116.47
ZV 20	112.64
ZV 25	106.60
PV70	117.42
PV80	109.65
PV90	112.64
PV100	110.66

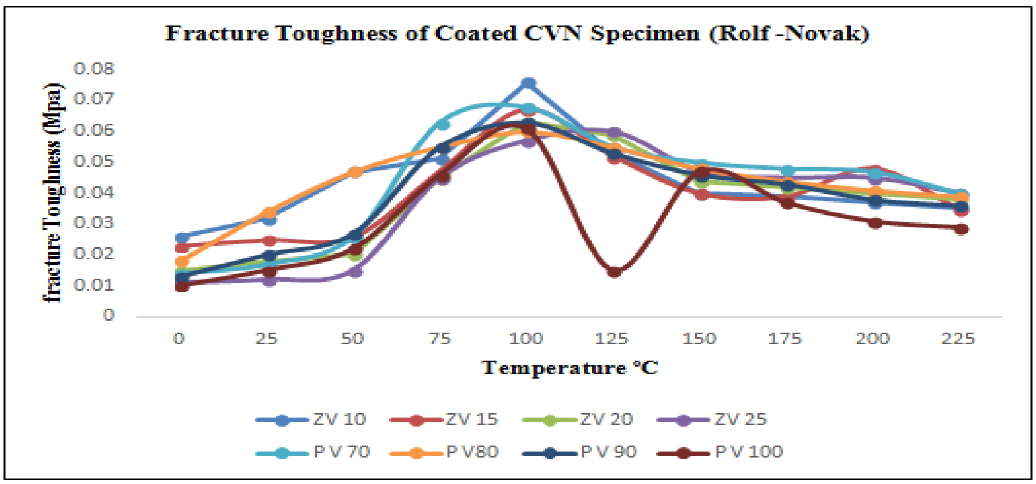

Fig4: Correlation of different material condition at 100ºC Temperature

6.0 CONCLUSION AND SCOPE FOR FUTURE WORK

It is seen that the behaviour of K_{IC} is similar to behaviour of impact energy, we can say charpy impact testing is the best suited method for determination of K_{IC}. The results are, for Zinc Plated V- Notched Specimens the Max.Fracture Toughness is achieved by Zinc Plated (10µm) specimen and Max.Fracture Toughness is achieved by Zinc Plated (20µm) specimen and for Powder Coated V-Notched Specimen the Max. Fracture Toughness is achieved by powder coated (70µm) specimen and Max. Fracture Toughness is achieved by powder coated (100µm) specimen. As service temperature increases, strength and K_{IC} increases up to certain limit after which it decreases drastically.As thickness of coating increases, strength of component increases up to some critical value of coating thickness, beyond which the strength will decrease. Up to critical value of thickness, and within the transition temperature range low carbon steel can be best used as structural material for aerospace, marine, automobiles and other engineering applications.In this paper, a generalized procedure to determine fracture behaviour of material under varied temperature and material conditions have been discussed. In the future, base metal and coating method can be changed to determine fracture behaviour of other materials. There is enough scope to analyze the nature of fracture using fractography analysis.

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