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TECHNICAL ARTICLE—PEER-REVIEWED

Fatigue Failure of Gears and Bearings During Processing of Rebar Steels

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Abstract The objective is to study fatigue failure of gears and bearings during processing of rebars and evaluate their performance under cyclic stresses. Mechanical vibration was measured on gears and bearings to determine efficiency and to avoid fatigue failure of components. These components are used during hot rolling to plastically deform steel billets and are exposed to cyclic and variable load stresses. The total amount of energy loss in the form of mechanical vibration was determined, and it was concluded that the materials selected for gears and bearings complied with the design criteria by failing progressively and not suddenly. Consequently, it was also concluded that the energy efficiency on reheating is strongly affected by fatigue failure of any of the components during hot rolling.

Keywords Fatigue · Gears and bearings · Energy considerations · Failure · Vibration · Rebar · Steel making

Introduction

The steel industry is one of the highest energy consumption worldwide. It is also an industry where energy is dissipated during continuous casting process through mold water cooling, spray water cooling and air cooling. The development of continuous casting technology has increased energy efficiency, but it faces some serious problems such as cracks, inclusions, segregation, oscillation marks and inhomogeneous solidification structure distribution [1]. The iron and steel industries account for 7% of total global CO_2 emissions. The principal steel producers in the world are China, Japan, USA, India and Russia. China produces and consumes 50% and 44%, respectively, of crude steel, and its power consumption is 9% of the entire society [2]. Mexico is an important iron and steel manufacturer and is the 13th largest steel producer in the world. In 2014, Mexico produced 19 million metric tons (MT) of crude steel, accounting for 1.16% of the world's crude steel production. It is also the first energy consumption for industrial use representing 14.3% of total industrial consumption [3]. The implementation of technologies in steelmaking has significantly lowered the energy consumption. The main objective of the study described here is to understand fatigue failure in the context of reducing CO_2 gases that are generated during processing rebars by analyzing energy that is wasted under certain scenarios. Energy systems are modeled to better define the maximum efficiency by using laws of thermodynamics, mechanical vibration concepts, materials concepts and materials failure analysis.

Thermomechanical Processing Efficiency

The thermomechanical energy efficiency for producing rebar steel requires optimization to reduce CO_2 emissions. It is modeled to meet the standards of ASTM A615 and A706 for grades 40 and 60 with yield strength of 280 and

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420 MPa, respectively, and tensile strength 1.25 times the yield strength or 420 and 620 MPa, respectively. The elements commonly used include carbon, manganese, silicon, copper, nickel, chromium, molybdenum, vanadium, columbium, titanium and zirconium [4, 5]. Equation 1 describes the maximum amount of carbon equivalent (CE) for weldability, and for ASTM 706, it should not exceed 0.55% [5]. Bars must meet an elongation of between 7 and 14% per every 200 mm in length [4, 5].

$$\text{C.E.} = \%\text{C} + \frac{\%\text{Mn}}{6} + \frac{\%\text{Cu}}{40} + \frac{\%\text{Ni}}{20} + \frac{\%\text{Cr}}{10} - \frac{\%\text{Mo}}{50} - \frac{\%\text{V}}{10} \tag{Eq 1}$$

Melting and Reheating Processing Energy

The highest energy consumption during steelmaking occurs during melting and reheating. The amount of energy consumed is dependent on the melting practice. Equation 2 is the amount of energy needed to raise the temperature of steel up to its melting temperature, and Eq 3 is the amount of energy needed to rearrange the molecular structure under the assumption of constant pressure, and heat transfer rate is identical along the three axes.

$$Q = mc_p\Delta T \tag{Eq 2}$$

$$Q = mL \tag{Eq 3}$$

$$Q_T = mc_p\Delta T + mL \tag{Eq 4}$$

Equation 4 is the sum of the energy needed to increase the steel temperature up to its melting point and the amount of energy needed to rearrange the molecular structure where Q_T is the total energy in kilo joules (kJ), C_p is the heat capacity $\frac{\text{kJ}}{\text{kg}*{}^\circ\text{C}}$ and is a measure of the amount of energy needed to raise the temperature to 1 °C on 1 kg of mass, ΔT is the temperature change in Celsius degrees (°C), m is the mass in kg and L is the latent heat of fusion or internal energy measured in $\frac{\text{kJ}}{\text{kg}}$. The heat absorbed by other materials and heat generated by technology are not being taken into consideration. Consequently, to obtain liquid steel under the following selected conditions with a heat capacity for steel (c_p) taken to be 0.461 $\frac{\text{kJ}}{\text{kg}*{}^\circ\text{C}}$, consider an average steel melting point of 1500 °C for recycled scrap. If an ambient temperature of 20 °C is taken for this analysis, it will give a Δ of 1480 °C, a latent heat of fusion or enthalpy constant (L) for steel of 272 kg and a mass of 1 ton or 1000 kg. The Q_T needed for melting a metric ton (MT) based on Eq 5 under the above-mentioned selected conditions is given by:

$$\begin{aligned} Q_T &= mc_p\Delta T + mL \\ &= 1000\,\text{kg} * 0.461\frac{\text{kJ}}{\text{kg} *{}^\circ\text{C}} * 1480\,{}^\circ\text{C} \\ &\quad + 1000\,\text{kg} * 272\frac{\text{kJ}}{\text{kg}} = 954{,}280\,\text{kJ} = 954.3\,\text{MJ} \end{aligned} \tag{Eq 5}$$

The liquid steel is poured into a ladle and billets are produced by continuous casting processing; hence, heat is dissipated and 686.8 MJ will be needed for solidification as shown in Eq 6.

$$\begin{aligned} Q_T &= mc_p\Delta T + mL \\ &= 1000\,\text{kg} * 0.461\frac{\text{kJ}}{\text{kg} *{}^\circ\text{C}} * (1600 - 700)\,{}^\circ\text{C} \\ &\quad + 1000\,\text{kg} * 272\frac{\text{kJ}}{\text{kg}} = 686{,}800\,\text{kJ} = 686.8\,\text{MJ} \end{aligned} \tag{Eq 6}$$

Another high-energy consumption studied is the reheating of steel billets. The reheating operation is intended to have a uniform temperature of billet for hot rolling, so that the stress is uniformly distributed during hot rolling. During this process, oxidation and decarburization may also occur on surface and carbon monoxide and carbon dioxide is generated [6]. The reheating process affects yield strength of steel, but it is desirable to remove superficial defects on the surface and increase material toughness and ductility. The maximum efficiency for reheating a billet is given by Eq 7 when the initial temperature is 20 °C and is reheated to its recrystallization temperature of 980 °C giving a ΔT of 960 °C. Thus, a 1000 kg mass is needed 442.6 MJ for reheating (Eq 7).

$$\begin{aligned} Q &= mc_p\Delta T = 1000\,\text{kg} * 0.461\frac{\text{kJ}}{\text{kg} *{}^\circ\text{C}} * 960\,{}^\circ\text{C} \\ &= 442{,}560\,\text{kJ} = 442.6\,\text{MJ} \end{aligned} \tag{Eq 7}$$

Therefore, the minimum amount of heat needed for producing a billet is the sum of Eqs 5 and 6 and it gives a total of 1641.1 MJ (Eq 8). In addition, when reheating is needed an extra of 442.6 MJ are added and totals 2083.7 MJ as in Eq 9. However, the challenge for engineering is to approximate to these numbers by selecting the most efficient procedure along with technology.

$$Q_T = 954.6\,\text{MJ} + 686.8\,\text{MJ} = 1641.1\,\text{MJ} \tag{Eq 8}$$

$$Q_T = 1641.1 + 442.6\,\text{MJ} = 2083.7\,\text{MJ} \tag{Eq 9}$$

Hot Rolling and Efficiency

Hot rolling is an expensive and very energy-consuming operation; hence, an attempt is made to keep rolling sequence and schedule to few steps as far as possible for obtaining the required shape and dimensions. However, hot rolling is not only for giving shape, but it is an important step in steel technology for ensuring correct dimensions, homogeneity of the mass and quality of the rolled product [7].

Rolling efficiency is influenced by the effectiveness of the rolling sequence. This process is repeated several times until the desired bar diameter is obtained. The induced stress elongates the grains parallel to the longitudinal length of the billet or bar and consequently its length is increased. Billets undergo deformation because of their exposure to external forces that exceed their yield strength. At 1600 °C, the representative modulus of elasticity and yield strength is 10% [8]. For grade 60 at a temperature of 1600°F, its yield strength is 42 Mpa, and a modulus of elasticity of 20 Gpa is obtained. The selected conditions for this analysis are for billets with a square cross section of 0.133 m sidelength and a mass of 1000 kg to maintain consistency in comparison for analysis.

Consequently, the cross-sectional area (CSA) is divided into multiple segments to calculate the axial forces needed to commence deformation on rolling by taking the maximum allowable stress or yield stress (σ_y) of 42 Mpa at a temperature of 900 °C. Then, after the CSA forces were gradually calculated, the minimum total amount of energy needed for plastic deformation was calculated, as shown in Table 1 based on change in length.

Therefore, the highest axial force needed during hot rolling occurs when its cross-sectional area is at its maximum value. In this scenario, it needed a force of 743.4 kN for a CSA of 0.0177 m^2. The highest energy consumption rate occurs at the beginning of rolling. In Fig. 1, the energy accumulated by small reductions on cross-sectional areas is indicated. Thus, an amount between 13 and 40 MJ for rolling processing is needed. In case there is misalignment between rolls and between rolling mills, the misoriented force is going to cause fatigue failure on mechanical drive train components.

Processing Equipment and Fatigue Failure Energy Analysis

In contrast, due to the high amount of load that is needed (Table 1) for rolling and plastically deforming a billet, it is important to maintain the mechanical system at best condition to avoid any misoriented force with the potential to cause any failure. The mechanical properties taken into consideration for materials selection of equipment used in steel industry are based on thermal stability, creep resistance, strength, hardness and corrosion resistance. Lubrication on gears and bearings is important to prevent a premature failure. Lubrication is essential for all gears and bearings subject to measurable loadings, and even for lightly loaded to reduce friction [9].

Table 1 Cross-sectional areas (CSA) ranging from an initial 0.0177 m^2 to lower CSA of 0.000129, and respective axial force needed to initiate deformation on billet with a yield strength of 42 MPa at 900 °C

	Cross-sectional area in m^2	Axial force needed (N)	Length (m)	Total energy accumulated (J)
		$\sigma_y A = F$ $42\ \text{MPa} * A = F$		$U = F \times \Delta d$
Initial billet	0.017700	743,400	7.47	0
	0.016000	672,000	8.3	579,852
	0.015000	630,000	8.8	949,452
	0.014000	588,000	9.4	1,345,452
	0.013000	546,000	10.2	1,771,914
	0.012000	504,000	11.0	2,233,914
	0.010500	441,000	12.6	3,025,914
	0.009500	399,000	13.9	3,609,492
	0.008000	336,000	16.5	4,648,992
	0.006000	252,000	22.0	6,496,992
	0.003500	147,000	37.7	10,456,992
	0.000900	37,800	146.7	26,472,992
Rebar #10	0.000819	34,398	161.2	27,021,300
	0.000700	29,400	188.6	27,963,780
	0.000500	21,000	264.0	30,181,380
	0.000300	12,600	440.0	33,877,380
	0.000200	8,400	660.0	36,649,380
Rebar #4	0.000129	5,418	1023.3	39,700,729

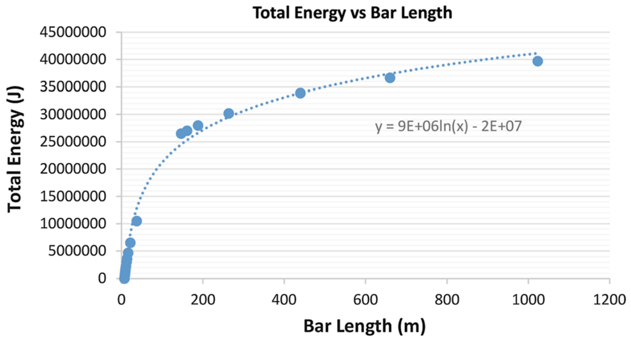

Fig. 1 Total energy accumulated for cross-sectional reduction (CSA) as a logarithmic function of bar length

The reliability of gears and bearings depends on their hardness values to avoid any surface defect that can initiate failure of material. Therefore, when contamination and abrasive particles get into lubrication oil, gears and bearings will resist more against inclusions and wear.

A typical gear train system used for rolling processing consists of a motor coupled to a speed reducer gearbox with an output coupled to a differential gearbox, as shown in Fig. 2. Therefore, in view of the number of components and contact points to deliver work, any imperfection within the system has the potential to initiate and propagate failure. The failure mode will be fatigue, impact, wear and stress fracture; these are caused by tooth bending, abrasive particles, shear stresses or when yield strength has been exceeded [10]. A commonly accepted minimum surface hardness for most bearing components is 58 HRC [10]. AISI 440C stainless steel which is suited for moderately corrosive environment has a maximum hardness value of 62 HRC. The drawbacks for this type of steel are that it has a maximum working temperature of 175 °C compared to 315 °C on CBS1000M. The 52100 steel through hardened is widely used for ball bearings, and 8260 for roller bearings. The carbide structure on 440C is coarser, making it softer than the 52100 series steel, and fracture toughness is about one half than 52100 [10]. The life and reliability of the system cannot exceed the life and reliability of the lowest live component in the system [11]. Moreover, XRF for chemical composition on an outer race bearing was obtained, and results were close to 52100 steel composition.

Consequently, XRF analysis was performed on a gear tooth fracture, and chemistry composition results were close to 41XX steel series; these steels have a composition of Cr 1.0% and Mo 0.25% and yield strength values between 740 MPa to 1860 MPa that depend on tempering temperature [12]. Therefore, mechanical vibration was measured to evaluate the actual conditions on gears and bearings when they are exposed to fatigue scenario.

Mechanical Vibration

Vibration is defined as small oscillations around an equilibrium point. The main characteristics of vibration are amplitude and frequency [13]. A vibrating system of any kind that is driven by and is completely under the control of an external source of energy is in a state of forced vibration. (3) Vibration in a mechanical system is a sign of inefficiency. Systems under forced vibration generate a frequency that defines the type of external and not desired forces that act against it.

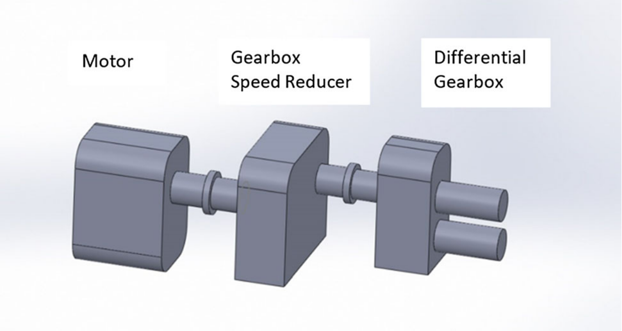

Fig. 2 Rolling mill gear train system

Any force acting in the undesired direction on a mechanical system will generate vibration as a form of energy, and this is directly proportional to the efficiency of the system. In addition, if this vibration exceeds the permissible stress intensity on material, which is usually 150 MPa, $\sqrt{m^2}$ will cause failure.

Energy Analysis and Fatigue Failure

Mechanical vibration was monitored on bearings' housings to evaluate the actual conditions of gears and bearings to predict failure for a rebar steel plant over a 5-year period. The equipment used for measuring, collecting data and for analysis was the Emerson CSI 2130 analyzer, the Emerson accelerometer model A0760GP and AMS Suite: Machinery Health Manager V5.61 software used for a more detailed frequency analysis.

A failure on a gear and a bearing starts on the material's surface, and it progressively deteriorates with time if no brittle fracture occurs as shown in Fig. 3a with insignificant or minimum wear on its surface. However, the undesired cyclic stresses act against the material at a continuous rate that initiates failure of material. This localized initiation of failure changes the vibration amplitude of the system and propagates as presented in Fig. 3b–d.

Material failure on gears or bearings starts when they are exposed to mechanical forces that exceed the yield strength along any of their three axes, or because fatigue failure was caused by cyclic loading. Mechanical vibration or cyclic stresses lead to fatigue failure of mechanical systems and the primary cause of failure is fatigue, the secondary cause is impact, the third cause is wear, and fourth is stress rupture [10]. The most common fatigue stresses are generated by misalignment, imbalance and looseness; the characteristic patterns observed on spectrums are shown in Fig. 4.

Another important frequency is generated by gears and is calculated by equation GMF = $N_T * \mathrm{RS}$ where GMF is gear mesh frequency in Hz, N_T is the number of teeth and RS is the shaft rotating speed in cycles per second or Hz units. In Fig. 5, the frequency of 243.7 Hz is generated by a 37 teeth gear rotating at a speed of 395 rpm (6.583 Hz). The amplitude and sidebands are monitored for any change in their behavior and tendency in the long term.

In addition, bearings are critical components in the industry that can cause significant monetary losses if failure occurs, they are designed to withstand high amount of

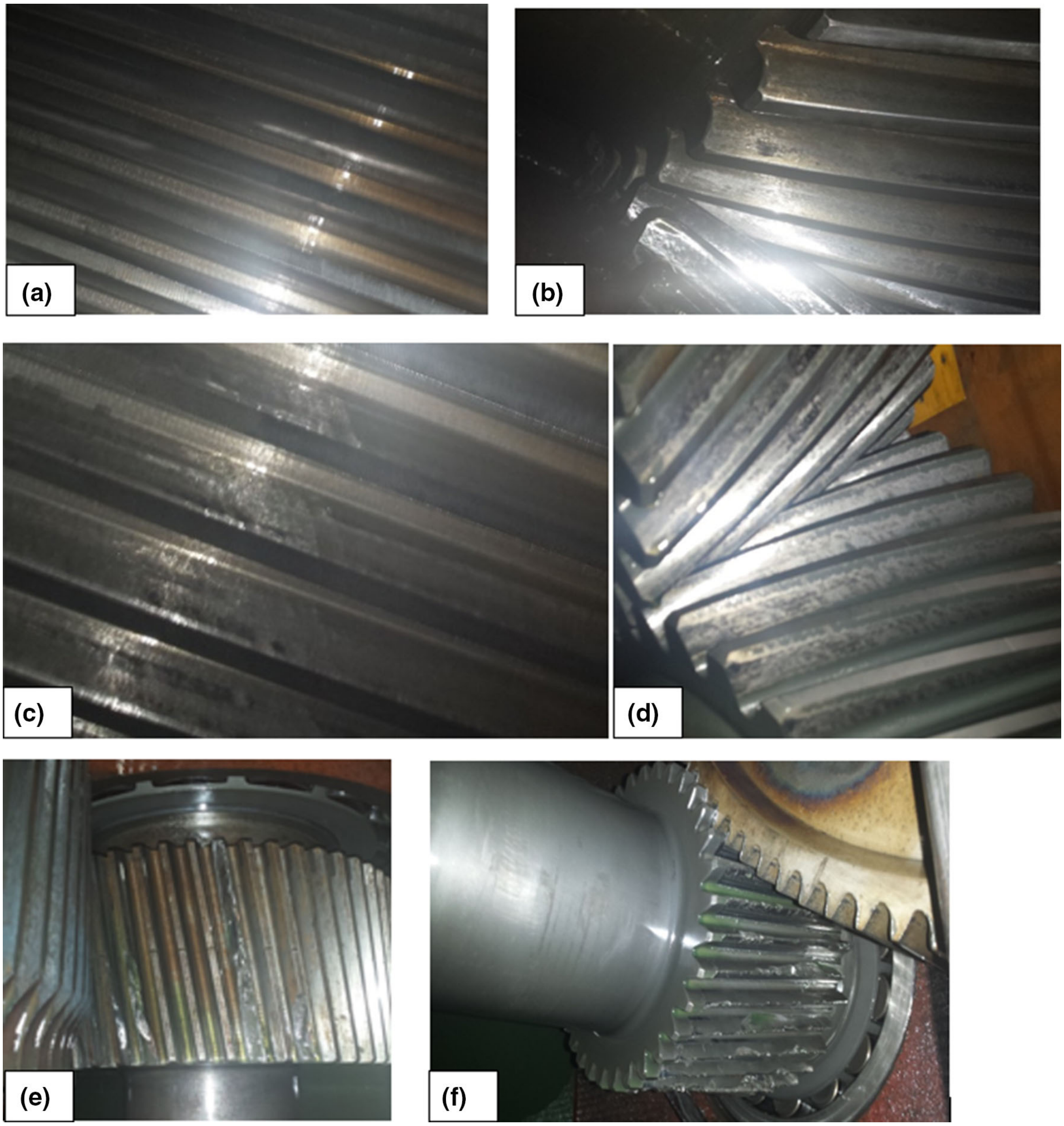

Fig. 3 Gears progressive failure stages. (a) Stage I—minimum amount of wear signs on gear surface. (b–d) Stage II—pitting and wear at different surface areas (surface failure initiation). (e–f) Stage III—fracture and/or deformation of gear's material

load acting in the radial and axial direction. However, if they are exposed to high vibration levels and to inconvenient ambient conditions failure will occur. Therefore, when a defect or imperfection is initiated on a bearing component with the exception of a seal, it generates a unique defect frequency and they are detailed in Eqs 10–13.

$$\mathrm{FTF} = \frac{S}{2}\left(1 - \frac{B_{\mathrm{d}}}{P_{\mathrm{d}}}\cos\theta\right) \text{ Track/Cage defect frequency} \tag{Eq 10}$$

$$\mathrm{BPFI} = \frac{N_{\mathrm{b}} * S}{2}\left(1 + \frac{B_{\mathrm{d}}}{P_{\mathrm{d}}}\cos\theta\right) \text{ Inner race defect frequency} \tag{Eq 11}$$

$$\mathrm{BPFO} = \frac{N_{\mathrm{b}} * S}{2}\left(1 - \frac{B_{\mathrm{d}}}{P_{\mathrm{d}}}\cos\theta\right) \text{ Outer race defect frequency} \tag{Eq 12}$$

$$\mathrm{BSF} = \frac{P_{\mathrm{d}} * S}{2B_{\mathrm{d}}}(1 - \left(\frac{B_{\mathrm{d}}}{P_{\mathrm{d}}}\right)^2 (\cos\theta)^2 \text{ Ball spin defect frequency} \tag{Eq 13}$$

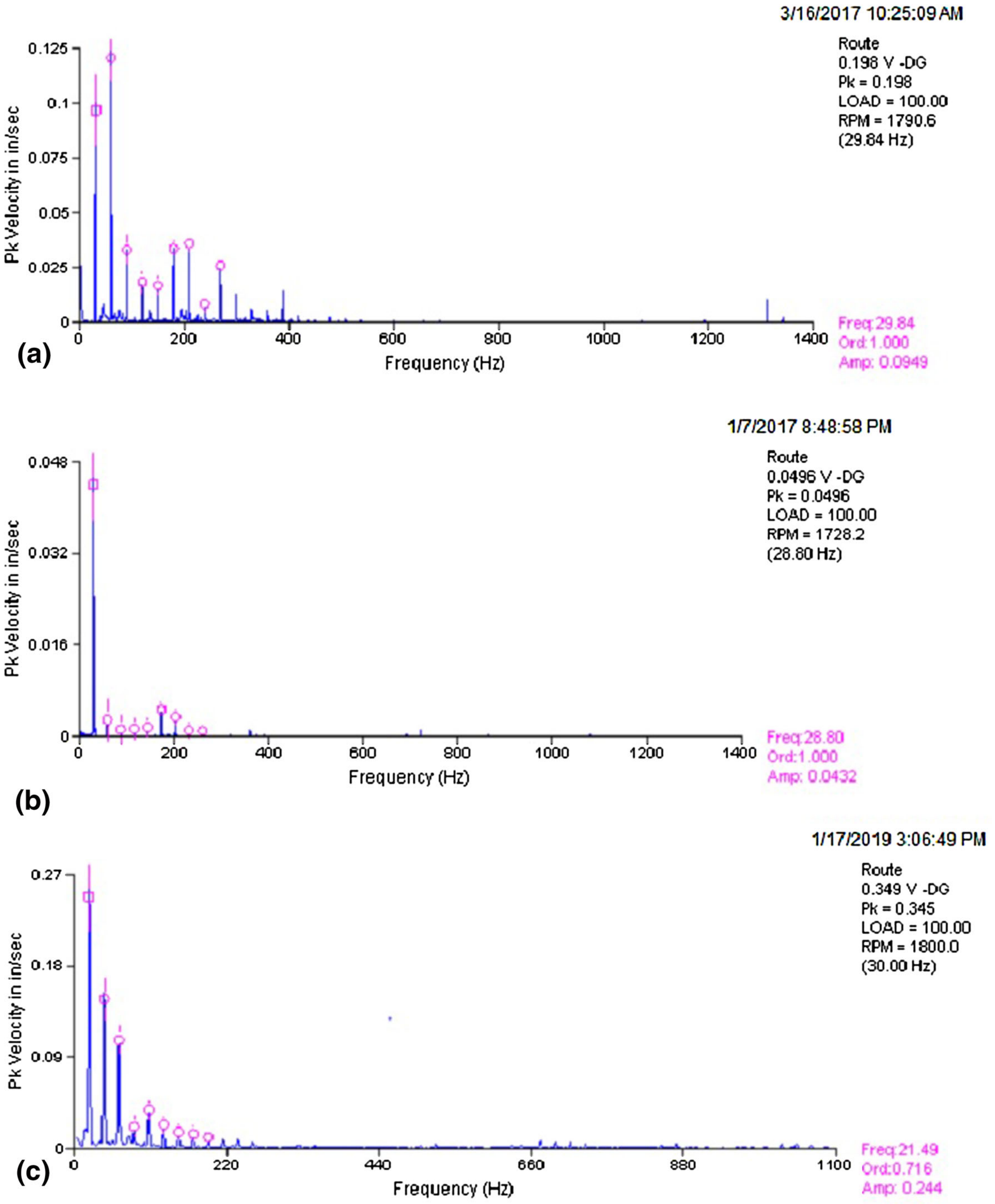

Fig. 4 (a) Misalignment cyclic stress occurring at a frequency of 29.4 Hz. (b) Unbalance cyclic stress generated at a frequency of 28.8 Hz. (c) Looseness pattern frequency at a rate of 30 Hz

where S = revolutions per second, B_d = ball or roller diameter, N_b = number of balls or rollers, P_d = pitch diameter, θ = contact angle.

The different stages described in Fig. 3 show how material surface failure tends to initiate and to propagate on gears and bearings, and these stages have been correlated to vibration levels based on a 5-year data. Consequently, Stage I is for normal and stable operating levels; in Stage II, the severity increases and material physical conditions may start to produce some defects, it is also the initiation to failure; Stage III corresponds to high vibration levels and is the unstable region, subsequently, at any time mechanical failure can occur. Furthermore, the range for Stage I is from 0.03 in/s to 0.06 in/s, Stage II is 0.07 in/s to 0.12 in/s

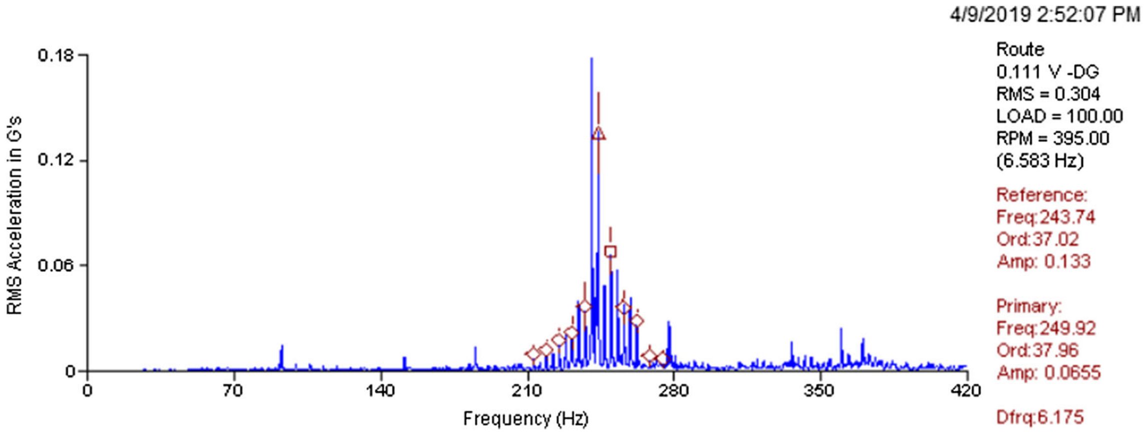

Fig. 5 Gear mesh frequency for a 37 teeth gear rotating at a speed of 6.583 rps

and for Stage III is greater than 0.13 in/s (Fig. 6). Reliability is strongly dependent on the operating procedure. The energy loss in the form of mechanical vibration was calculated using four case studies on gearboxes used in rolling mills and is presented in Table 3. These gearboxes are designed to multiply the input torque between 7.2 and 16.52 from a driven force motor of between 600 HP and 1000 HP, and these gearboxes have a mass of 4000–6500 kg. The total amount of work energy is calculated from Eq 14, where W is work energy in joules (J), F is force in Newtons (N) and d is distance in meters (m).

$$W = F * d = m * a * d \tag{Eq 14}$$

Hence, the displacement of one period was multiplied by the number of revolutions per minute times 60 to obtain the amount of distance traveled by the oscillations generated by vibration in one hour, and this is presented in Table 2. As a result, a mass of 6500 kg was considered and multiplied by the respective acceleration from spectrums and waveforms obtained from software analysis. The total amount of energy per hour, per day and per 6 month period was obtained (Table 3).

Therefore, the total number of cycles at which equipment was exposed to high mechanical vibration levels and considered here as being present in Stage III was calculated and is presented in (Table 4). The number of cycles generated by the turning speed of driven force was calculated for a 3-month and a 6-month period. Hence, based on assigned rpm input on gearboxes, they all reached at least 43.8E+06 and 8.8E+07 cycles for 3-month period and 6-month periods, respectively. Mechanical vibration has a significant impact on the reliability of gears and bearings used in the steel industry for hot rolling of rebars. It affects the efficiency if failure occurs during production. The highest impact occurs on reheating due to the energy consumption to maintain billets at a temperature of at least of 960 °C. Stefan Boltzmann equation for radiation energy transmitted is given by Eq 15 where P is power in watts (W), σ is Boltzmann constant of $5.67 \times 10^{-8} \frac{\mathrm{W}}{\mathrm{m}^2 * \mathrm{T}^4}$, e stands for emissivity and A is material surface area in m^2. Hence, if e of 0.90 for steel is taken into consideration for a billet surface area of 4.01 m^2, as presented in Eq 16, a total power of 564,030 W is needed.

$$P = \sigma A e (T^4) \tag{Eq 15}$$

$$\begin{aligned} P &= \sigma A e (T^4) \\ &= 5.67 \times 10^{-8} \frac{\mathrm{W}}{\mathrm{m}^2 * \mathrm{T}^4} * \left(4.01\ \mathrm{m}^2\right) * [1255°\mathrm{K}]^4 \\ &= 564,030\ \mathrm{W} \end{aligned} \tag{Eq 16}$$

Thus, 2030.5 MJ is the total amount of energy needed (Eq 17) to maintain a steel billet for 1 h on reheating at a temperature of 960 °C as given by Eq 17.

$$\begin{aligned} &P \\ &= 2,030,508,000\ \mathrm{J} = 2,030.5\ \mathrm{MJ} \end{aligned} \tag{Eq 17}$$

In the four cases of study, it was concluded that there is a significant percent difference on mechanical vibration energy between before and after the replacement of new or better set of gears and bearings. In three out of four cases

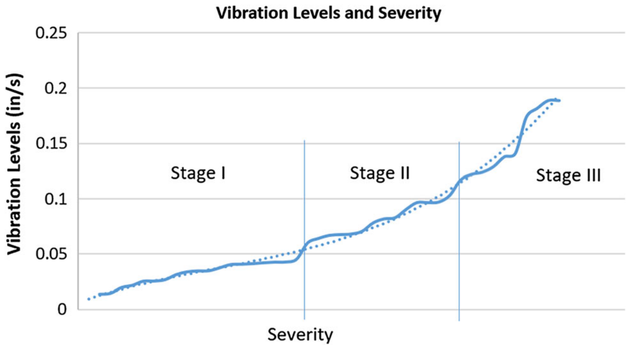

Fig. 6 Vibration levels and severity stages

Table 2 Total displacement calculation in one hour

		Velocity		Displacement		
		in/s	m/s	Mils per cycle	Meters per cycle	Total displacement in 1 h (m)
Gearbox 1						
Before	Horizontal	0.1300	0.00330200	18.600	0.000472440	9.581033
3/26/2015	Vertical	0.0594	0.00150380	5.643	0.000143332	2.906777
338 rpm	Axial	0.1820	0.00462280	25.650	0.000651510	13.212623
After	Horizontal	0.0592	0.00150368	10.230	0.000259842	2.962199
7/25/2015	Vertical	0.0156	0.00039624	5.893	0.000149682	1.706377
190 rpm	Axial	0.0434	0.00110236	135.360	0.003438144	39.194842
Gearbox 3						
Before	Horizontal	0.2380	0.00604520	41.560	0.001055624	22.358116
2/16/2015	Vertical	0.2210	0.00561340	2.530	0.000064262	1.361069
353 rpm	Axial	0.1380	0.00350520	18.650	0.000473710	10.033178
After	Horizontal	0.0437	0.00111000	13.470	0.000342138	6.815389
6/22/2015	Vertical	0.0179	0.00045470	9.985	0.000253619	5.052090
332 rpm	Axial	0.0230	0.00058420	4.697	0.000119304	2.376532
Gearbox 4						
Before	Horizontal	0.1540	0.00391160	13.430	0.000341122	8.739546
8/15/2017	Axial	0.3670	0.00932180	17.610	0.000447294	11.459672
427 rpm						
After	Horizontal	0.0340	0.00086360	6.084	0.000154534	4.218767
9/12/2017	Axial	0.0414	0.00105156	9.365	0.000237871	6.493878
455 rpm						
Gearbox 5						
Before	Horizontal	0.1750	0.00444500	62.400	0.001584960	35.566502
4/10/2017	Axial	0.2030	0.00515620	39.740	0.001009396	22.650846
374 rpm						
After	Horizontal	0.0360	0.00091440	16.860	0.000428244	9.712574
7/16/2017	Axial	0.0408	0.00103632	11.710	0.000297434	6.745803
378 rpm						

existed a reduction in between 68 percent and 96 percent and on one case the reduction was between 31 and 91 percent in terms of energy generated by the movement, or displacement by vibration in relationship to a reference point. Therefore, the design criteria to avoid brittle fracture are satisfied under American Gear Manufacturers Association (AGMA).

Conclusion

In conclusion, the melting and reheating of steel are the two highest energy consumers within the steel industry. It is needed at least an amount of 2083.7 MJ for melting, solidification and reheating a metric ton (MT) of steel. In contrast, it is needed 2030.5 MJ when failure occurs on any mechanical component to maintain billet at the proper

Table 3 Mechanical vibration energy and percent difference

		Acceleration			Energy in Joules		
		G's	m/s^2	1 h	1 month	6 months	
Gearbox 1							
Before	Horizontal	0.14	1.3720	2,079,052	62,371,564	374,229,384	
3/26/2015	Vertical	0.0607	0.5949	273,478	8,204,354	49,226,124	
338 rpm	Axial	0.198	1.9404	4,054,870	121,646,107	729,876,640	
							% difference
After	Horizontal	0.0638	0.6252	292,926	8,787,774	52,726,643	− 86
7/25/2015	Vertical	0.00968	0.0949	25,602	768,059	4,608,352	− 91
190 rpm	Axial	0.0459	0.4498	2,788,459	83,653,783	501,922,699	− 31
Gearbox 3							
Before	Horizontal	0.408	3.9984	14,138,981	424,169,426	2,545,016,554	
2/16/2015	Vertical	0.191	1.8718	402,936	12,088,086	72,528,517	
353 rpm	Axial	0.138	1.3524	2,146,052	64,381,573	386,289,436	
							% difference
After	Horizontal	0.0569	0.5576	601,071	18,032,125	108,192,748	− 96
6/22/2015	Vertical	0.0157	0.1539	122,940	3,688,203	22,129,215	− 69
332 rpm	Axial	0.0256	0.2509	94,299	2,828,965	16,973,790	− 96
Gearbox 4							
Before	Horizontal	0.044	0.4312	596,025	17,880,741	107,284,447	
8/15/2017	Axial	0.0624	0.6115	1,108,357	33,250,699	199,504,192	
427 rpm							
							% difference
After	Horizontal	0.0238	0.2332	155,627	4,668,813	28,012,880	− 74
9/12/2017	Axial	0.0351	0.3440	353,292	10,598,765	63,592,588	− 68
455 rpm							
Gearbox 5							
Before	Horizontal	0.0419	0.4106	2,309,819	69,294,564	415,767,386	
4/10/2017	Axial	0.0513	0.5027	1,801,045	54,031,346	324,188,074	
374 rpm							
							% difference
After	Horizontal	0.0168	0.1646	252,910	7,587,306	45,523,837	− 89
7/16/2017	Axial	0.0201	0.1970	210,161	6,304,835	37,829,008	− 88
378 rpm							

Table 4 Number of cycles with given rpm

	Number of cycles			
rpm	Cycles per 1 h	Cycles per 1 day	Cycles per 3 months	Cycles per 6 months
338	20280	486720	43.8E+06	8.8E+07
358	21480	515520	46.4E+06	9.3E+07
427	25620	614880	55.3E+06	1.1E+08
455	27300	655200	59.0E+06	1.2E+08

temperature for hot rolling for every hour on down time. Based on mechanical vibration analysis and tendencies as a measurement for fatigue, gears and bearings tended to fail progressively by the increase in vibration levels over time. In addition, there exists a high potential to reduce energy and material consumption if mechanical vibration analysis is performed and applied properly.

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